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PRINCIPLES AND TECHNIQUES OF ULTRASONIC INSPECTION

Harold C. Psillas

ABSTRACT

Ultrasonic inspection for subsurface flaws is widely used in American industry. This report reviews the general principles and specific techniques of ultrasonic testing. The information is based on a review of the technical literature plus the experience of the Quality Assurance Department at Sandia Corporation in applying this nondestructive testing technique to quality evaluation programs.

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PRINCIPLES AND TECHNIQUES OF ULTRASONIC INSPECTION

INTRODUCTION

Considerable interest in ultrasonic methods of testing materials by agencies involved in nondestructive testing led the Sandia Corporation Quality Methods Organization to a comprehensive study of the techniques, equipment, and application of ultrasonics as used by various industries on the West Coast. The findings of this study are presented in this technical memorandum for the purpose of providing a better understanding of the scope and the limitations of ultrasonic testing.

Ultrasonic Inspection Methods

Seven methods of ultrasonic inspection are in use or under development today. Actually, only four of these methods are sufficiently varied to require separate equipment. The other three are actually variations of standard forms of ultrasonic testing. These are presented here in the order in which they will appear in the body of the report.

1. Contact Pulse Echo
2. Immersion Pulse Echo
3. Shadow Immersion
4. Resonance
5. Frequency Modulation
6. Contact Transmission
7. Immersion Transmission

The presentation of the order is, of course, arbitrary and will vary in importance with specific use and availability of equipment. The immersion methods of testing are actually variations of pulse echo, transmission, and frequency modulation methods.

Theory of Ultrasonics

The term "ultrasonics" is used in acoustical circles to refer to the vibrational wave frequencies which are beyond the hearing limits of the human ear. This range lies above 20,000 cycles and has been generated as high as 5×10^8 cycles.

The laws for the audible sound range, however, are also valid for the ultrasonic range with the exception of certain phenomena which occur only in ultrasonics. As the frequency of the sound waves is increased in any given media, the length of the waves decrease proportionately. The minuteness of the sound waves of higher frequencies makes possible the use of ultrasonics on materials of granular structure with very little effect from the grain boundaries.

In materials of good sound capacity, the usable frequency of ultrasonics increases, thus permitting inspection of small granular structures.

The ultrasonic testing techniques used at present utilize the ultrahigh frequency range of 200 KC to 25 MC. The primary purpose of ultrasonic testing is to detect internal flaws or foreign substances having various acoustic impedances in an otherwise homogeneous mass. In some instances, use of the vibrational quality of sound waves is made to determine the thickness of given materials. This is especially true of the resonance method, which, in a piece of known acoustical quality, can determine the thickness of the piece by determining its resonant frequency. Resonant frequency varies directly with the thickness of the material, but the speed of sound in the material must be determined for this information to be useful.

The piezoelectric effect, a phenomenon in which some crystals, when subjected to pressure or tension, develop electrical charges across the crystalline surfaces, has been utilized to advantage in ultrasonic inspection. At present, the piezoelectric effect derived from crystalline solids whose structures present elements of symmetry of the trigonal group are used as the source of ultrasonic energy. Such salts include quartz, tourmaline, rochelle salt, etc. The finished crystal used in ultrasonics is called the transducer, or search crystal. The complete crystal circuit is also referred to as the probe.

THE CONTACT PULSE ECHO METHOD

Discussion

The pulse-echo system is normally applied in two methods: contact and immersion. Although these two methods are similar in operation, they vary considerably in resolution and application. They will, therefore, be treated as separate methods for clarity in presentation and discussion. In contact pulse-echo testing, the most satisfactory way to transmit the ultrasonic waves from the crystal is by coupling through a thin film of SAE 10 oil or light transformer oil. An electronic generator creates ultrasonic waves by supplying high-frequency AC voltage to a quartz crystal. The crystal radiates these waves into the material and also acts as a receiver to detect back reflections. An electronic amplifier applies the reflected signal to a cathode ray oscilloscope, which measures the time interval between transmission of the outgoing and reception of the incoming waves. A typical screen pattern will show two peaks, or "pips", one representing the initial pulse return from the surface of the material, and the other representing the reflection from the other side. A discontinuity will result in a pip occurring between the two peaks. A calibrated square wave can be superimposed on the screen to locate the discontinuity fairly accurately.

The initial pulse will appear to the left of the screen while the final pulse will appear to the right. The flaw will appear at a distance between these pulses that is directly proportional to the location of the flaw in the specimen.

The Crystal

Due to the high frequencies of ultrasonics used in the inspection of materials, the use of a piezoelectric transducer for sending purposes is necessary. The crystal is extremely sensitive to pressures, as was pointed out previously, and releases electrical energy when deforming pressures are applied. By reversing this procedure, an electrical charge placed across the crystal will cause it to deform in conformance with the electrical charge. By pulsing the crystal in this method, it can be caused to vibrate at its resonant frequency, emitting sound waves rapidly to the surrounding environment at a rate equal to its natural frequency, (Figure 1).

The crystal vibrates at this frequency for about two-millionths of a second, resulting in a brief spurt of sound waves into the coupling material. When the material stops vibrating, there is a period of silence in which returning sound waves are received by the crystal, (Figure 2). These sound waves are converted into electrical energy in a reverse manner from which they were formed.

Introduction of the Sound Wave

The contact pulse-echo method utilizes a direct contact between the crystal transducer and the material under study. In order to transmit the waves from the crystal to the material and receive the waves from the material to the transducer, a liquid connector is necessary. This is caused by the phenomenon that very short sound waves for all practical purposes, will not travel through air. Also, the source and the solid to be examined must be coupled together acoustically to affect a transfer of energy with minimum losses. This condition is attainable when the source and the solid in question are of approximately the same acoustic impedance. However, a good impedance match is very difficult to attain, for, regardless of the degree of smoothness achieved at the interface, an intervening layer of air is always present. This layer of air, having a radically different acoustic impedance from the source and the material being tested, prevents adequate matching even though the layer is only molecular in thickness. An example of this is given in the early works of Sokolow, who found that the close fit between the surfaces of two Johansen blocks is not sufficient for good acoustic coupling.

After passing through the crystal material boundary, the ultrasonic energy enters and passes through the material to the opposite boundary, where it is reflected back to the same transducer from which it originated and is reconverted to a voltage by a reverse affect to the crystal.

TRANSMISSION OF SOUND WAVES

FIG. 1

RECEPTION OF SOUND WAVES

FIG. 2

(a.) INTIMATE CONTACT

(b.) FREE SLIDING

FIG. 3

302 006

-7-

It may then pass into a mixer to be projected on a phosphorescent screen. In understanding the path of the sound wave, it is well to remember that the laws governing the reflection of light also govern the behavior of sound energy in a homogeneous mass.

The problem of transferring ultrasonic energy from the crystal to the material with acoustic matching is not as undesirable as it seems. Without it, the principle of ultrasonic testing would be voided. The fact that voids and inclusions are bound to have some acoustic differences is precisely what ultrasonic testing is based on. Therefore, the problem is only one of voiding the crystal-material interface of all gases to eliminate as much feedback at this point as is possible.

Couplant Between Crystal and Test Piece

Refraction and reflection may be appreciably decreased by the use of a suitable medium interposed between the crystal source and the material specimen that will exclude the air and effect a better impedance match. This coupling medium may be a liquid such as oil, soapy water, liquid soap, mercury, mercury amalgams, or a viscous solid such as plasticine. Water, unless the material is completely immersed in water, is not a good couplant for contact scanning. This is because of a tendency on the part of the water to flatten out and flow off the piece due to its low viscosity. If water is used, an adequate supply should be kept running over the contact surfaces. A most efficient and convenient coupling arrangement is a thin film. A liquid which "wets" the surfaces involved is the most effective since it also tends to remove loose material. The customary technique involving the use of a film of oil between the transducer and the specimen is based on these facts as well as on ease of application and operation with the oil, (Figure 3).

Surface Preparation

In previous sections of this memo, the assumption of a smooth surface on the piece to be tested has been made. Any surface having irregularities in the order of $1/20$ or less of the wave length employed may be considered smooth. Conditions of roughness not overcome by the liquid or viscous solid media must be improved by grinding or other surface preparation prior to testing. In this fact lies the greatest limitation to contact ultrasonic inspection. The minimum amount of surface preparation recommended on samples for ultrasonic inspection or testing is as follows:

A surface roughness of not more than 125 microinches rms should be maintained on the contact surface. The use of a portable disc grinder has proved to be the most advantageous and economical method for preparing surfaces of greater roughness.

2. Loose scale is detrimental and must be removed before inspection. Areas where scale has been indiscriminately chipped due to handling are not satisfactory for ultrasonic inspection. The area should be either all tight scale or clean smooth metal.
3. Foreign material, such as dirt, grit, grease, slag, etc., must be removed before the coupling fluid is applied.

Detection of Flaws

Where the reflection method of detection is used, the inspector looks for an echo from a discontinuity. Where no discontinuity exists in a homogeneous mass, there is no echo signal. A typical block diagram, based on the Sperry Products model of the UR Reflectoscope gives a satisfactory picture of the inspection mechanism, (Figure 4).

The single transducer technique is utilized by pulsing the sound wave. That is, a wave pulse is transmitted, after which the transducer is free to "listen" for echoes from discontinuities. However, there is enough of the initial pulse of sound energy picked up by the receiving circuit to obscure the reflections from flaws in the first 1/2 to 3/4 inch of the material under investigation. Therefore, discontinuities close to the sending transducer, as well as all others smaller and in line with the initial flaw, are generally not detected unless the testing is accomplished from two opposing faces of the work piece, (Figure 5).

Particularly in the case of metallic media, variations in acoustic impedance may be encountered in the form of structural variations and voids which give rise to reflection and scattering of the sound beam. When the grain size of a metallic material is sufficiently large in relation to the wave length of the sound, it is difficult, if not impossible, to pass the wave energy through the material. In general, materials having a worked or otherwise refined grain structure can be more readily penetrated than as-cast material.

Interpretation of Findings

The interpretation of test results is primarily based upon a knowledge of the basic theory regarding ultrasonics along with some actual experience in reading the defects.

With regard to the effect of voids on the propagation of ultrasonic energy through a medium, the size, shape, and orientation of these voids with respect to the beam must be considered. Larger voids intercept more sound energy and therefore will reflect more energy.

TYPICAL BLOCK DIAGRAM
FIG. 4

302 009

EFFECTS OF BLIND DEPTH

FIG. 5

- A. INITIAL PULSE DEFLECTION.
- B. FLAW ECHO DEFLECTION.
- C. BACK ECHO DEFLECTION.
- D. TIME-DISTANCE MARKERS.

UN SOUND MATERIAL

FIG. 6

- A. INITIAL PULSE DEFLECTION.
- B. FLAW ECHO DEFLECTION.
- C. BACK ECHO DEFLECTION.
- D. TIME-DISTANCE MARKERS.

NON-PARALLEL BACK SURFACE

FIG. 7

- A. INITIAL PULSE DEFLECTION.
- B. FLAW ECHO DEFLECTION.
- C. BACK ECHO DEFLECTION.
- D. TIME-DISTANCE MARKERS.

SOUND MATERIAL

FIG. 8

302 010

Figure 6 illustrates a typical cathode ray tube pattern as obtained in the contact pulse-echo method using the single crystal technique. The significant parts of the pattern are the calibrated sweep axis (D), appearing as a notched horizontal line when the marker is operating, the initial pulse deflection at A, the flaw echo deflection at B, and the back surface deflection at C. The notches in the sweep line at D represent units of the time lag, which may be correlated with the velocity of sound through the material tested to indicate distance in that material. Figure 7 illustrates the stretching of the pattern that results from nonparallelism of the two opposing faces of the test piece. Since the length of time passage is greater, the appearance of the back surface on the screen will appear proportionately later.

The lack of a deflection of the cathode ray trace between A and C, as shown in Figure 8, may indicate the absence of any discontinuity of sufficient size to be detectable at the wave length used. Higher frequencies may indicate that flaws are present. If, however, a portion of the back echo also disappears without a flaw indication, then there is a strong possibility that a flaw is present but situated in such a manner as to deflect a greater portion of the sound energy away from the probe crystal. The absence of all deflections except that at A (see Figure 9) may be due to any one of several causes. The material may be (a) too coarse-grained, (b) too porous or, (c) may have a back surface that is either too rough or not sufficiently parallel to cause an echo in the crystal. Figure 9 (d) illustrates unpenetrable material. In any of these cases, reverting to a lower frequency may solve the problem, although some loss of resolution must be expected. A side face search may prove that a flaw exists at an extreme angle, causing a loss of the echo through reflection and absorption.

If a second deflection appears to the left of the proper position for the back surface reflection and the latter is smaller, (Figure 10A), or virtually absent, (Figure 10B), a discontinuity similar to a lamination and large enough to reflect the entire beam is probably present. If the crystal is placed upon, but not acoustically coupled to, the material being tested to affect a transfer of energy, the A pulse will be long and unreadable, (see Figure 11). This long pulse is caused by a reverberation of the sound energy within the crystal, called "ringing". The amount of "ringing" or widening of this pulse is indicative, therefore, of the degree or efficiency of the acoustic coupling to the material being tested.

In addition to the conditions described above, there may be numerous higher order reflections as shown in Figure 12. The number of these reflections gives a rough indication of the transparency of the material with respect to sound energy, or, again, an indication of coupling efficiency. Except where extreme attenuation is experienced, these "echoes" will appear on the screen. This is especially true in the case of lighter alloys of aluminum. These may be cleared from the

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LOSS OF BACKFACE ECHO

FIG. 9

302 012

(A.)

(B.)

LARGE FLAWS

FIG. 10

POOR CRYSTAL - SPECIMEN CONTACT

FIG. 11

~~302 013~~
302 013

- A. INITIAL PULSE DEFLECTION.
- B. FLAW ECHO DEFLECTION.
- C. BACK ECHO DEFLECTION
- D. TIME-DISTANCE MARKERS.

HIGHER ORDER REFLECTIONS

FIG. 12

- A. FRONT COMPENSATOR.
- B. REAR COMPENSATOR.
- C. SPECIMEN.
- D. COUPLING MEDIUM AT INTERFACE.

302 014

CURVED SPECIMEN WITH COMPENSATING PLATES

FIG. 13

screen as desired through circuit adjustment. It must be remembered, however, that these echoes are more sensitive to attenuation and are, therefore, valuable in detecting porosity or other sound-scattering flaws.

Complex Reflection Methods

It is often necessary to inspect pieces having curved surfaces or otherwise presenting no flat surface upon which the crystal may be placed. If the contact area between the crystal face and the surface of the work is large enough to pass sufficient energy into the work, no problem exists. However, if it is evident through trial that inadequate coupling is being attained, further modifications of technique must be employed.

It is possible to refract ultrasonic waves by means of specially constructed curved crystals and/or metallic "lenses". This method utilizes the refraction principle to advantage in the transmission of ultrasonics from a flat crystal into the curved surface of a test specimen. Two aluminum compensating pieces are used to correct the curvature of the specimen surface and present a surface to which a flat crystal may be applied. Such a technique would be practical for inspection only when a large number of like parts or like surfaces are to be tested. Figure 13 illustrates a lens of this nature. Figure 14 illustrates the use of a V-wedge to introduce sound through couplants at a particular angle parallel to a side face. This type of angle or "carom" testing is especially useful when working on materials with thin cross sections in the magnitude of less than one inch.

Penetration Characteristics

The ability of ultrasonic waves to penetrate large sections (up to 50 feet in depth) has been the major feature of this method of testing since no other means of doing this are available at present. This does not limit the use of ultrasonics to large areas or great depths. By scanning an area, the inspector can obtain a reasonable idea of the size and the shape of the discontinuity and venture a fairly accurate opinion regarding its proper classification. Areas containing segregation, fine porosity, or clusters of small inclusions, prove more difficult to identify. Such areas will often reflect no signal because of internal scattering. However, they will give rise to a greatly attenuated boundary reflection. In extreme cases, the back face echo may be entirely missing. This latter fact implies that some discontinuity is present. The nature of such a discontinuity can sometimes be deduced if the inspector has some idea regarding its extent or its location. An accurate picture as to the location and extent may be gained by testing from two or more surfaces of the material.

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FIG. 14

STANDARD SC TEST BLOCK FOR TUNGSTEN CARBIDE

FIG. 15

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Laminations and such flaws lying parallel to the direction of rolling on rolled stock cannot be conclusively detected as such from the end surfaces. This is due to the comparatively small surface presented to the probe. For this reason, two-directional study is recommended providing the directions are with the grain and the surfaces are perpendicular to each other rather than parallel.

Properly used, ultrasonics will prove more valuable and selective than X ray in location and determination of flaws. This is especially true of hairline cracks or laminations.

Accuracy

Tests run by the Quality Assurance Organization in conjunction with Los Alamos Scientific Laboratory indicated that the accuracy of the Sperry Ultrasonic Reflectoscope Model UR used in contact testing compares favorably with the Betatron instrument in locating subsurface flaws. Results of testing the same pieces on both instruments under identical conditions revealed that the Reflectoscope will pick up any flaws indicated by the Betatron. Consequently, the ultrasonic tester may be considered of comparable accuracy as the Betatron for inspection purposes. The reflection method will locate internal discontinuities which present a reflecting surface to the sound beam as it passes through the material. The minimum size discontinuity which can be detected is one having projected lateral dimension roughly equal to about 0.1 per cent of the distance from the crystal to the defect. For example, at six inches, the smallest detectable defect would be 0.006 inch; while at 10 feet, it is possible to locate a 1/8-inch defect. The accuracy of measurement will be upwards of roughly 1/8 inch again. By moving the crystal on the surface, the extent of the discontinuity can be outlined.

The reason for the variation of resolvable size in distance from the probe lies in the sound attenuation properties of the material. By amplifying the sound received sufficiently to reinstate it to its original power state, a constant-sized defect may be assumed with a given return signal. This time-distance amplification has been accomplished in immersion pulse-echo equipment.

Calibration

Since the speed of transmission and wave length varies in different materials and under the daily variance of ambient conditions, calibration of the ultrasonic tester to the condition of the specimen material from time to time is necessary. A test block, made of the same material as the test specimen and drilled with different sized holes is necessary to calibrate the ultrasonic instrument, (Figure 15).

Procedure for Calibration

The recommended procedure for use in setting up the contact-type tester at the beginning of each inspection period may be divided into steps as follows:

1. Place the transducer in steady and firm contact with the surface of the test block, (Figure 15). The transducer should be in a neutral area with no holes in its path. A good couplant, such as light transformer oil or SAE 10 oil should be applied in a complete but thin film over the test surface, (see Figure 16).
2. With the reject control in the "off" position, set the sensitivity control so that the "noise" from the material structure begins to show on the base line as in Figure 17. Adjust the sweep length so that the back reflection appears at the right side of the base line.
3. Advance the reject control until the "noise" disappears, and the pattern appears as in Figure 18. The "square wave" marker imposed scale, which permits the measurement of distance from the test surface to any reflecting surface, may be imposed now if needed.
4. Locate the transducer opposite the 1/2-inch drilled hole, or above it when the drilled surface of the block is downward. The pattern should resemble Figure 19, the reflection from the hole almost covering the height of the oscilloscope screen.
5. Locate the transducer above the 1/4-inch hole and, if necessary, adjust the reject control so that the pattern resembles Figure 20.
6. Check the 3/16 and 1/8 inch holes with Figures 21 and 22. Further small adjustments of both the sensitivity and reject controls may be necessary in order to obtain the correct proportions between all the different sizes of drilled holes.

Test Blocks

Test blocks for special materials such as Figure 15 should be prepared in advance of the test program. Recent tests have indicated that both the material used and the thickness of material affect calibration. In stock materials of nominal thickness, standard blocks are commercially available for instrument calibration. Two commercially available standards are the Alcoa Blocks (Aluminum Co. of America, available in aluminum or steel) and the Hitt Blocks (Ultrasonic Testing and Research Laboratories, available in aluminum, steel, or special order).

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FIRM CONTACT IN NEUTRAL AREA

FIG. 16

COUPLANT FILM

PROJECTION OF
HOLE PATTERN

302

0.15

NOISE

FIG. 17

CLEAR

FIG. 18

20

1/2" HOLE

FIG. 19

1/4" HOLE

FIG. 20

3/16" HOLE

FIG. 21

1/8" HOLE

FIG. 22

The Alcoa blocks feature a constant height with varied diameter holes at a standard depth ($3/4$). The Hitt blocks feature constant diameter holes at a standard depth ($3/4$ inch) with varied heights. By using both sets of blocks, corrections may be made for both depth and size, setting the flaw echo to a go no-go height. However, conditions outlined in the limitations should also be considered.

Limitations

It should be realized that even careful calibration will not ensure that discontinuities within a part can be accurately measured as to shape and size. Approximations must be made depending upon the distance of the discontinuity from the transducer, the location with respect to edges of the part, and the type of defect as judged by the appearance of its indication on the oscilloscope. However, with proper attention to all of the calibration details, flaw sizes can be determined to an accuracy of 25 per cent.

One of the greatest limitations is encountered in reading defects on the oscilloscope screen. It is often difficult to determine the extent of a flaw in a piece. A given sized flaw close to the front surface of the specimen will appear much larger than a similar sized flaw close to the back surface. This condition is illustrated in Figure 23. If the two conditions illustrated were repeated at infinite increments of flaw depth, a curve similar to line "E" will result. This is an inherent fault of the Sperry Model UR Reflectoscope which has been corrected somewhat on immersion ultrasonic equipment. Such a condition is caused by attenuation of the sound energy in the piece itself. Attenuation of the wave from the source to the point of entry is not considered, since it is essentially the same in both conditions. Returning to Figure 23, it is apparent that the sound energy must travel further to flaw "D" than to flaw "C", therefore there is a greater loss of sound energy. A similar condition exists on the return trip of the flaw reflection. The signal loss in the transition from the front surface through the couplant to the crystal is not constant but more a percentage of the remaining energy at this point, so losses at "D" would be proportionately less than at "C". However, at the beginning of the curve, this equalization is not sufficient to make up the difference. Hence, a smaller signal is received at point "D". However, this "percentage-type" loss at the interface does result in somewhat flattening the curve at the later stages.

The limitation just described can be minimized by proper study in the preparation of standardization curves for the various more commonly used materials and/or more critical special materials. This will enable the operator to define specifically whether a flaw is larger or smaller than the reference defect.

TIME - ENERGY LOSSES

FIG. 23

REVERBERATION

FIG. 24

Another limitation predominant in contact scanning is the "blind" area caused by ultrasonic reflection and reverberation at the interface. Figure 24 illustrates how the sound wave reverberates in diminishing strength extending the time echo to such a degree that flaw echoes returning from some point within $1/2$ to $3/4$ inch of the surface are completely hidden. Although, on raw materials, there are allowances made for "skinning" the material before the finished product is obtained, there is seldom an allowance made of such magnitude. It is therefore necessary, in the majority of cases, to search both sides of a piece. Further, on complex forgings or castings, or on complex extrusions, it is almost impossible to determine flaw except in those areas providing parallel surfaces. Curvatures require crystals with identical opposite radii. Except where a particular radius is of great importance, or much used in a major lot of production, it is normally too expensive to obtain curvature crystals.

The UR Reflectoscope has the inconvenient feature of providing a picture very difficult to interpret. The initial and back face echoes are greatly exaggerated on the screen because of reverberation. Likewise, the flaw echo presents a pip that is too wide-based, a condition which is further complicated by a very fuzzy boundary of the pip. These conditions make an approximation of flaw depth the only method of resolution available. However, in most cases, a good approximation of flaw depth is all that is required.

Present contact scanning equipment operates at the lower frequency range used in ultrasonic testing. This range, from 500 KC to 10 MC, while better for penetration purposes, does not allow for the improved resolution of higher frequencies. Where possible, the greatly improved clarity of immersion testing should be used.

Uses

The contact method of ultrasonics is primarily intended to detect subsurface flaws. At present, it is not intended as a depth measuring instrument because of the wide-banded surface indications. Since considerable strides have been made in the accuracy and resolution of immersed testing, contact testing can only be recommended where immersion testing is impractical. Properly used, contact scanning can prove a valuable instrument to both production and inspection.

Contact scanning is widely used by metal mills, railroads, construction companies, and field inspection points where immersed testing proves impractical because of size, stage of assembly, fixed condition of assembly, or inaccessibility to any but the more portable of equipment. Cast ingots and pigs are checked for porosity and homogeneity prior to extrusion or rolling. Railroads utilize contact scanning to determine fatigue value on rolling and stationary stock such as axles, rails, rods, welds, etc. Construction companies and field inspectors primarily

use ultrasonics on raw materials acceptance.

Any material possessing fair to good sound transmission qualities may be checked ultrasonically. Parallel surfaces are required along with a 125 mi rms minimum finish. Thicknesses of at least twice the bandwidth of the front face echo are required for proper inspection, and laminations must have continuous bond. Angle shooting is not recommended on laminar items since oblique angles aid in almost complete angular deflection of the sound energy, resulting in coverage of only the top lamination, (see Figure 25).

A. STRAIGHT SHOT

B. ANGLE SHOT

EFFECTS OF LAMINATIONS

FIG. 25

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THE IMMERSED PULSE ECHO METHOD

Discussion

The second and more recent method employed in ultrasonic inspection is the immersed pulse-echo method of testing. This system shows promise of proving itself the most useful form of ultrasonic testing of all the methods available.

Unfortunately, the immersion method of testing requires a considerably larger complement of equipment than does the contact method. To counteract this, the accuracy and dependability of results through the use of this method has led to large and adequate installations of immersion equipment.

Douglas Aircraft, Inc. found immersion inspection of incoming raw materials so profitable that they installed a tank 13 feet wide by 40 feet long to accommodate the larger sheet and plate stock. The tank was installed with automatic scanning devices controlled remotely from a raised platform by the Aetna-engineered remote time-setting device. Above the control panel are the Electrocircuits, Inc. Model 424 Immerscope (A-scan), (Figure 26), and the Model 425 (B-scan), (Figure 27). Cost estimates for reproducing this establishment run upwards of \$25,000 less Electrocircuits Products and material handling equipment.

North American Aviation, Inc. came up with an unusual innovation on a field problem involving a large aluminum plate. A wooden frame of 2 x 4 inch material was erected around the plate. The edges were tarred to retain water. Figure 28 illustrates the finished frame and plate. The assembly was then filled with water and checked with a long boom on the end of which was a dolly arrangement which held the crystal below the water level, (Figure 29). The readings were recorded on a Sperry Model UR Reflectoscope with the Wide-Band Converter.

Cost estimate studies made by North American showed the reason for the intense interest in ultrasonics by the various aircraft companies. A check was run on 1008 pieces of various shapes, sizes, and materials. Careful timekeeping was made on inspection time to determine the cost of inspection. Determination of machining costs was made on each piece machined afterwards and extended to cover the rough cast or as-forged pieces rejected. An approximation of the results of this test follows:

Total Pieces	1008
Accepted Pieces	<u>768</u> (approx.)
Rejected Pieces	240 (approx.)

MODEL 424

HEIGHT 17 INCHES
 WIDTH 14 INCHES
 DEPTH 24 INCHES

A-SCAN
 (ELECTROCIRCUITS, INC.)

FIG. 26

MODEL 425

HEIGHT 31½ INCHES
 WIDTH 24 INCHES
 DEPTH 24 INCHES

B-SCAN
 (ELECTROCIRCUITS, INC.)

FIG. 27

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NAA PLATE FRAME

FIG. 28

NAA CRYSTAL DOLLY

302 0208

FIG. 29

Cost of Machining Total Pieces	\$839,000
Cost of Machining Accepted Pieces	<u>550,000</u>
Cost of Machining Rejected Pieces	\$289,000
Cost of Total Inspection (Incl. Equip.)	<u>39,000</u>
Savings on Machining	<u>\$250,000</u>

This estimate does not take into consideration the added savings realized through fewer customer complaints, and the increased customer confidence in the product. The importance of this factor was rather dramatically pointed out when one aircraft company almost dissolved after several unfortunate incidents occurred involving a part previously considered unimportant and overdesigned. Failure of this part resulted in immediate stoppage of military contracts until sufficient safeguards were installed to preclude reoccurrence. A post-mortem on the parts revealed that minor inclusions and unhealed porosity in the original material, which was too scattered and small to appear on X ray, were at fault. A rapid introduction of ultrasonics solved the problem of a safeguard and led to rejection rates of mill materials ranging from 10-50 per cent.

This program of tightening requirements by the one company led to tightened requirements by the rest. The result of the problem was to flood the mills with rejected material. In turn, the mills have initiated research and control programs to improve material quality and to reduce rejection rates. The results of ultrasonics, primarily embodied in the immersion pulse-echo method, are creating new and better grades of materials to meet the rigorous requirements of modern industry.

The Crystal

The operation of the ultrasonic immersion crystal is identical to the contact crystal. There are certain structural differences, however, which make them noninterchangeable.

First, the underwater crystal is smaller and considerably more sensitive than the contact crystal. The contact crystal is sturdier by necessity, to take the wear and tear dealt to it by the human hand against hard and abrasive surfaces. To withstand this, the delicacy and sensitivity had to be sacrificed. The underwater crystal has other problems to be faced, such as waterlogging, underwater short circuiting, and increased sound reverberation within the crystal housing.

As a result, the structures are different. Sound dampeners are used in underwater crystals, resulting in a longer crystal housing. The greater sensitivity permits the use of smaller crystals, resulting

in a frustum of a pyramid. Also, due to the greater freedom of motion in immersion testing, only one crystal is necessary for a given frequency. Angle crystals are not needed.

Introduction of the Sound Wave

The immersion pulse-echo method utilizes indirect contact between the crystal and the material being inspected. The waves are transmitted from the crystal to a connecting fluid such as water or oil. The inspected material is completely immersed in the fluid with at least three to four inches of the fluid rising above the highest point to be inspected. The fluid here acts much in the same manner as the coupling fluid did in the contact scanning method, only there is more of it and contained by the tub to a height permitting free horizontal movement. The theory of contact scanning generally holds for immersion scanning, except that mobility, resolution, and automation possibilities are gained.

Here, again, the choice of coupling fluid must be made with an eye to good acoustical matching. When water is used on aluminum, for example, 88 per cent of the sound energy is lost on the aluminum-water interface. This is a drastic, but not a hindering, loss. Further, the use of a detergent (normal household detergent such as Trend, Tide, etc. will suffice) is necessary to permit complete wetting of the interface surfaces. The crystal housing should be shaken gently to assure that no air is trapped between the crystal and the fluid.

Couplant Between Crystal and Test Piece

The choice of required coupling fluid is considerably more difficult to make in immersion scanning due to the comparatively vast quantities of the fluid required. Where small quantities sufficed in contact scanning, more expensive fluids such as light motor oil with additives could be used. In immersion scanning, the cost and quantities of fluid are more likely to influence the choice more than the increased acoustical match to be gained by more expensive materials.

For all practical purposes, water is the best choice for an immersion fluid. It is inexpensive, available in large quantities, translucent for better visibility of the immersed material, and permits marking of defects with grease pencils without removing the part from the bath. It also gives excellent acoustical matching with most materials. The acoustic impedance of water is just slightly higher than the more expensive oils, and the slight difference will actually make little difference insofar as resolution or accuracy is concerned.

However, it must be remembered that water has a tendency to collect air bubbles as it is being warmed to room temperature. It is therefore advisable to keep the water temperature at some point above room temperature to keep the air bubbles from forming and adhering to the work

surface. This will prevent spurious indications. The temperature should be determined to require a minimum of heating for cost purposes without overlooking operator comfort. Preservation of the operator's dexterity is important, since the sensitive controls of the electronic equipment depends on the operator's sense of feeling.

Surface Preparation

Contrary to requirements of contact scanning, the surface finish of the part need not be kept smooth. The only requirement here is that the variations do not vary so extremely that the front face echo disappears entirely through reflection and scatter. A gentle saw-tooth pattern (Figure 30) not varying more than ten degrees from normal should be considered a maximum. However, should the surface prove rougher than this and the front face echo disappears entirely, no surface preparation should be attempted. Instead, a tilting of the search crystal until the front surface returns should be attempted (see Figure 31). The effect of large changes in the height of the surface, whether due to waviness as is found on as-forged parts, or due to rough saw cuts or broaching, is not great. Depending on whether this waviness is on the front or back surface, the image on the A-scan screen tends to "float", depending on the orientation of the surface with the main water bang (crystal to water contact).

Loose scale in immersion scanning, as it was in contact scanning, is detrimental to the inspection. On the other hand, tight scale is desirable, since it tends to increase the flatness of the search surface. Figure 32 illustrates both of these conditions.

Referring to Figure 23 (A), which greatly exaggerates the situation for clarity in presentation, it becomes obvious that there is a greater likelihood that large air spaces can be contained under the loose scale. Tight scale (Figure 32 (B)) is more likely to cling to the surface of the metal. In some cases, the air space beneath the loose scale will completely stop the sound wave, or so seriously alter it that a portion of the surface gives indications of nonexistent flaws. While the tight scale will also show a surface flaw by increasing the front face signal, it will not appear as though the flaw were elsewhere. By keeping a surface more normal to the search crystal, tight scale is actually doing more good than harm. Consequently, loose scale should be removed and tight scale should be left on unless further finishing is contemplated. Consolidated Vultee Aircraft Corporation removes all scale, for example, by rough milling or broaching where it can be accomplished in one pass. This leaves a rough surface, but still more than adequate for immersion inspection.

Presentation

The presentation of the immersion method of scanning is considerably clearer and more accurate than the contact pulse-echo method. Immersion scanning

GENTLE SAW TOOTH PATTERN FROM ROUGH CUTTING OR MACHINING OPERATION

FIG. 30

TILTING OF SEARCH CRYSTAL FOR FRONT ECHO LOCATION

- 1. MAIN WATER BANG.
- 2. INITIAL SURFACE ECHO
- 3. FLAW ECHO
- 4. BACK SURFACE

■ TRAPPED AIR & OR WATER
 $\Delta X \rightarrow \frac{1}{8}$

(A) LOOSE SCALE

(B) TIGHT SCALE

302 633

EFFECTS OF SCALE ON MATERIAL

techniques have evolved to such a degree that they have made the method the fastest, most accurate and most useful on a greater cross section of industrial materials than any of the other ultrasonic techniques.

Several reasons for the sudden rise in popularity of immersion testing are the introduction of wide-band conversion, B-scan, and C-scan capabilities. These capabilities are outlined below, giving a general outlook for possible combinations to be used in various problems.

A-Scan — The A-scan is the term used to denote the visual method used in contact testing. Essentially, it is a point trace of the sound path through the material. Figure 33 illustrates the points along the sound wave which become predominant along the A-scan, (also referred to as an A-trace). Point "A" is known as the "Main Bang", or the reflection of sound energy returning into the crystal after having traveled an infinitesimal distance beyond the crystal. In contact scanning, this factor does not appear separately, but is intermingled with the front face echo which occurs almost instantaneously. Also, in contact work, the term A-scan is seldom used since it is the only means available to read the indications.

After point "A", at a time lag of Δt required by the sound wave to travel through the water column, comes the "front face echo". This echo is the reflected energy from the surface nearest the search crystal. This surface need not be normal to the search crystal as is shown in Figure 25, but should, also, not be radically oblique.

Points "C" and "D" appear on the screen in accordance with their orientation to the crystal face, depending on material thickness and flaw depth. The pip heights are relative and are determined by the amount of energy reflected by the flaw echo "C" and the "back face" reflection "D". It is wise to point out that the A-scan screen presentation is essentially the same as was shown in contact work.

Wide-Band Conversion — Wide-band conversion is a little publicized electronic means of converting the somewhat difficult image of the contact equipment to a high-frequency, clear picture on the A-scan. Figure 34 illustrates the difference in the presentation. Of course, it must be understood that the illustrations are based on average cases of separate items at different locations. They are not intended to convey true before and after studies.

The increase in the resolution with wide-band conversion is due primarily to the clearer presentation of the higher reflections and the damping out of many of the side echoes from the oscilloscope.

A - TRACE
FIG 33

(A.)
SPERRY IMMERSION
METHOD

(B.)
UR REFLECTOSCOPE WITH WIDE BAND CONVERTER

A. MAIN BANG	D. BACK FACE ECHO
B. FRONT FACE ECHO	E. BASE LINE
C. FLAW ECHO	F. UNCOMPENSATED MAX. STANDARD SETTING. (VARIES WITH MATERIALS)

SPERRY U.R. REFLECTOSCOPE

FIG. 34

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The presentation is made by a solid green trace on the cathode ray tube, caused by the availability of higher operating frequencies.

The wide-band converter can be used with great advantage on the Sperry Model UR Reflectoscope when used in immersion testing. This equipment provides frequencies of 5, 10, 15, 20 and 25 megacycles to the normal 0.5 - 5.0 megacycles of the reflectoscope. It also allows a separation of the front face-back face echoes or the front face-flaw, flaw-back face traces on the cathode ray presentation, and reduces the horizontal width of the indication. This allows greater resolution of the flaw depth.

B-Scan -- The B-scan assembly is made up of a combination of instruments. Where the standard Sperry UR Reflectoscope is used, a wide-band converter must also be used to convert to higher frequencies. B-scan can, at present, only be adapted to high-frequency immersion testing. Where no Sperry unit is presently available, an Electro-circuits, Inc. Immerscope is recommended. This unit is outlined below. However, the Sperry unit may be used as an alternate providing wide-band conversion does not affect the contact-type uses and portability.

The actual B-scan unit is a large screen T-V unit (Figure 27) produced only by Electro-circuits, Inc. of Pasadena, California. It is an electronic circuit that develops cross-sectional views of the metal being inspected and increases the inspection speed in routine material testing. The fluorescent coated screen retains the image, allowing a "memory" period in which the operator may catch fleeting impressions of defects even if his attention is momentarily attracted.

The B-scan assembly is primarily a production unit for production inspection, but it has been used successfully in laboratory quantity work. It is particularly valuable in the detection of flaws that cannot be detected with gamma radiation equipment. Figure 35 illustrates B-scan presentation as compared to A-scan. Figure 36 shows how actual parts will appear on a B-scan screen.

C-Scan -- The C-scan consists of a recording mechanism operating simultaneously with the A-scan mechanism making permanent recording of the flaw on the paper. It is achieved through the use of automation units which are necessary to present true plots, and presents a plan view of the defect. Figure 37 illustrates C-scan.

Frequency Modulation -- Frequency modulation in ultrasonics has the same connotation as it does in radio work: reception of higher quality. Frequency modulated sound waves are useful in the immersion testing of high-attenuation materials. Although this is not an immersion pulse-echo method, it is mentioned here as a useful item in immersion testing in general.

B-SCAN

SECTION A-A

A-SCAN

B-SCAN COMPARED TO A-SCAN PRESENTATION

FIG. 35

(A) ACTUAL CONDITION

(B) B-SCAN PRESENTATION

FIG. 36

A. LAMINATION IN PLATE

B. A-TRACE OF DEFECT

C. B-TRACE OF DEFECT

- ① FRONT SURFACE
- ② LAMINATION
- ③ BACK SURFACE

D. C-TRACE (PLAN VIEW)

THE ENTIRE SURFACE OF THE PLATE
MUST BE SCANNED TO OBTAIN THE
PLAN VIEW.

C-SCAN PRESENTATION

FIG. 37

Detection of Flaws

In the immersion pulse-echo method of testing, reflection of sound energy is again the primary detection factor. Where no reflection exists, no detection is possible. Here, as in the contact method, it is also possible to suspect a defect by the lack of reflection. However, the true nature of the defect and its location are not determined.

The principle of pulsing the transmission with the reception periods in the immersion method is identical to that used in the contact method. However, considerably less of the sound energy reflected from the initial surface is received. Also, higher frequencies are used in immersion testing, giving greater clarity to the oscilloscope presentation.

At present, two companies are producing A-scan immersion equipment. The Sperry UR Reflectoscope, diagrammed in Figure 4, may be converted to higher frequencies by the addition of wide-band conversion, an Electrocircuits, Inc. product. This converts the somewhat irregular presentation of the Reflectoscope to a fine-line continuous presentation.

Where the Electrocircuits Immerscope is used, considerably clearer images and greater resolution can be obtained. Resolution is the ability to determine the position and relative size of the defect in the specimen.

In general, the depth of flaw indication from either the back or the front reflection is in direct ratio with the actual depth of the flaw from the front or the back surface of the piece being examined. There is considerable disagreement, however, as to where along the curve on the screen presentation this measurement should be made. The Sperry UR Model Reflectoscope without wide-band conversion gives a trace difficult to interpret and measure.

The method recommended by the Electrocircuits Immerscope handbook suggests that readings be taken from peak to peak. Since the Immerscope image is a bright green phosphor continuous line, it is possible to determine the peak exactly within the limits of line thickness. Figure 38 illustrates the Immerscope presentation and method of measurement.

Measurements are normally made by use of a scribed clear plastic grid over the cathode tube, with the A-scan base set at the beginning of the test to coincide with the scribed base, and the front face echo with a scribe perpendicular to the base. This provides a definite line from which measurements may be made. Figure 39 illustrates a sample of such a grid which may be used for ratio purposes. Figure 40 illustrates the marker circuit presentation on the Immerscope. Care should be used when using the marker circuit to assure that a flaw indication is not reduced or obliterated in its use.

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- A = MAIN CRYSTAL-WATER BANG
- B = FRONT FACE ECHO
- C = FLAW ECHO
- D = BACK FACE ECHO
- E = HARMONIC BACK FACE ECHOES
- F = SCRIBED PLASTIC BASELINE
- G = COMPENSATED MAX. STANDARD SETTING.
- H = SCRIBED MARKER

FORMULAS:

$$\text{DEPTH OF FLAW} = Y_2 = \frac{X_2 Y_1}{X_1}$$

HEIGHT OF FLAW = GO-NO GO BASIS

ELECTROCIRCUITS, INC. IMMERSCOPE

FIG. 38

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- (A) HORIZONTAL BASE
- (B) VERTICAL BASE
- (C) REJECT LINE

GRID MARKER EXAMPLE

FIG. 39

MARKER CIRCUIT

(TURN ON ONLY AFTER SIZE OF FLAW HAS BEEN DETERMINED)

FIG. 40

In immersion testing, the accuracy of the equipment is not impaired by varying the distance of the probe from the search surface. The same relationship exists between the flaw echo and the front and back surfaces. There are, however, minor modifications that are required to compensate for this condition. Figure 41 shows two typical conditions which can occur to cause this variation in distance. In Figure 42, the varying of the distance can be compensated for by adjusting the height of the probe to bring the image back on the screen. This is a manual adjustment, since no method of lowering or raising the probe without first releasing it from the manipulator has been devised as yet. There are several ways of approaching the problem illustrated in Figure 43. Since the tendency will be for the back surface to slide towards the front surface, use of a higher frequency may be desirable to spread them out again. This compensation may not be necessary unless a flaw is detected. In the situation presented in Figure 44, it is normally advisable to invert the piece and study it from the flat (or nearly flat) surface. This precludes a variation in the water column, and permits the back surface to move towards the front surface. The back surface is not held to a scribed mark and is otherwise unimportant unless it is reduced in the vertical plane or disappears entirely.

On an irregular piece, the varying surface or surfaces will, in effect, "float" on the screen always keeping a direct ratio from section to section between the material front and back surfaces. If the material thickens, the echoes will "float" outwards, presenting a larger space between surface echoes. This space represents the material thickness. As the material thins out, the reverse occurs.

A general rule to follow is to keep as much normal to the work surface as is practical for the best results. This does not always give a true image of the defect, but close scrutiny of the screen for defections or loss of available back echo will indicate when several angles will be required.

In the case of Figure 44, if inverting the piece is unhandy or impossible, then the surface may be scanned with an additional setup as illustrated in Figure 45. This will raise the sloped surface to coincide with the horizontal, resulting in a reduction or loss of back surface echo.

Interpretation of Findings

All the information obtained concerning the conditions within a sample of metal will be presented visually on the screen in the form of echoes, recorded in accordance with their arrival at the transmitter. In order to translate this information for flaw analysis, the operator must be able to interpret quickly and accurately what he sees.

(A.)

(B.)

EFFECTS OF DISTANCE OF MATERIAL FROM PROBE

FIG. 41

FIG. 42

FIG. 43

POSITION 2, BACKFACE DISAPPEARS

FIG. 44

POSITION 2, FRONTFACE DISAPPEARS
AT EXTREME ANGLES

FIG. 45

BACKFACE ECHO DISAPPEARS

High-speed ultrasonic sound waves follow the same laws as light, and have similar reflection and refraction properties. In the illustrations shown to this point, refraction was omitted for simplicity in presentation. However, it should be remembered that this condition does exist and must be taken into account in order to accurately locate the defect and explain a consistent loss of back surface echo.

It will also be noted that, at times, multiples can be noted on the screen of the front or back surface echoes, as well as the flaw echoes. This is due to good penetration or the crystal being too close to the work piece. Sound reverberates in a solid homogeneous piece much in the same manner as light inside a glass box. Some of the light will pass through the glass, while other segments will reflect back into the piece to renew the cycle. Of course, these will return to the receiver at a much later time and will normally appear off the screen. Sometimes as many as four multiples will occur.

It would be impossible to attempt to illustrate every possible variation you may find on the screen. However, it is possible to illustrate several general cases into which the great majority of patterns will fall. The operator will find it simple, with practice, to classify the presentations as he gains experience, even though there are variations in the minor details of the trace.

Below are outlined several typical patterns which will be encountered. It is understood, of course, that the instrument has been preset to the maximum acceptable flaw using standard test blocks.

Case 1 -- The first example, as illustrated in Figure 46, is a relatively smooth-surfaced rectangular or round block with parallel surfaces. The sample is placed beneath the search crystal and approximately perpendicular to it. In this simple case, no difficulty will occur to prevent perfect reception of both front and rear surface echoes. Porosity in the sample is assumed at a minimum.

Flaw indications will appear between the front and back echoes. The time delay and sweep control (in units where these controls are available) is adjusted so that the front and back surface pips are spaced as widely as possible on the screen. By increasing the spread to a maximum readable value, the operator is assured of maximum accuracy in reading. The range markers or a previously scribed plastic grid is of great value in obtaining the relationship of flaw depth to material thickness.

Taking an example where the sample is two inches thick and a flaw exists at approximately two-thirds below the front surface of the piece, the screen presentation will show the initial (front) surface echo at the left. It is assumed here that the main water bang and multiples have been removed from the surveillance of the screen by spreading and proper positioning of the probe.

FLAW BETWEEN PARALLEL SURFACES

FIG. 46

FLAWS IN MACHINING STOCK

FIG. 47

The back surface echo, having the longest time of travel, arrives last and is situated at the extreme right. The flaw, located below the approximate center, has an echo which appears between the two flaws in proportion to its true location in the part. If it is slightly above center, it will appear slightly to the left of true center on the screen, and so forth. In most cases, such as finished parts or raw materials not specifically scheduled for a given machining or forming operation, it is sufficient to report the depth of flaw as beginning at one inch of depth, in the center, or otherwise roughly approximated. At times, it is necessary to determine the location more accurately. For example, Figure 47 shows a piece of raw material scheduled for a certain amount of machining. In this position, it is necessary to know that the flaw is neither above center, thus remaining in the piece after machining, nor at center, thus leaving an exposed flaw. When it is located accurately, special instructions on the "skinning" of upper and lower surfaces can accompany the piece to the machinist, resulting in a saving in scrap and, possibly, in machining effort.

Where the piece is inverted originally, and the flaw is shown above center (Figure 48) a search should be made along the bottom surface to assure that the flaw does not penetrate too deeply for use (Figure 48 inset).

Where the defect is as large or larger than the effective area of the crystal, virtually all of the sound energy will be reflected from the flaw and the back surface will disappear, (Figure 49).

Figure 50 (A) illustrates the condition where the back surface disappears or is reduced, yet the flaw echo is below the maximum. This illustration is used to point out the wisdom of "angle" shooting into all flaws to obtain maximum flaw height, (Figure 50 (B)).

Case 2 — Other situations encountered are those in which the back surface of the test sample is not parallel to the front surface. When the sound waves reach the back surface, they will be reflected in the same manner as a beam of light reflects off of a glossy surface. If the angle of the back face, the material thickness, and the crystal area combine to cause the sound to be reflected away from the crystal, then the back surface will disappear. Figure 51 illustrates such a condition.

In this case, all flaws located should be studied from several angles to determine the true magnitude of the defect. At times it will be difficult to determine whether the second pip represents a flaw or a back surface reflection. In all probability, unless the back surface is constantly changing or extremely rough, the second pip is a flaw. If there is a question involved, a quick check with the range marker will indicate which it is. The flaw will appear at a thickness less than the indicated thickness

LOCATION OF FLAW FOR ACCEPTANCE

FIG. 48

FLAW LARGER THAN EFFECTIVE CRYSTAL AREA

302 050

FIG. 49

A.

B.

FIG. 50

302 051

ANGLED BACK FACE

FIG. 51

of the material. Figure 52 illustrates how such a check might be made.

Case 3 -- In coping with the situation in which material depth and attenuation characteristics combine to such an extent that all of the sound waves are absorbed, the electronic range marker is of great help. It must be remembered that the back face echo of the material will be completely absorbed, and any pip to the right of the initial echo probably represents a flaw. A close relationship of distance must be obtained through either test or standard blocks to determine the location of the defect in the piece. Figure 53 illustrates a typical example of such a situation. If the flaw is at a location from a side surface at a depth less than full attenuation depth, a side search may be attempted to locate the defect, (see Figure 54). Of course, the depth must be estimated prior to the side study in order to determine whether it is worth while continuing the search.

Case 4 -- In testing a seam weld on a piece of thin-walled tubing (up to approximately 0.125 inch), it is normally cumbersome to follow the weld longitudinally with ultrasonic sound waves. Also, the use of a "gimmal" type dolly, Figure 55, is suggested where the length is roughly over six feet long, since positioning of longer lengths is difficult.

An acute angle of approach is necessary to determine the purity of the weld. The behavior of ultrasound at acute angles in such that some of the sound waves will be reflected from the unit and lost. Referring to Figure 56, it is noted that the sound waves at entry are reflected at the initial surface away from the probe. As a consequence, the initial echo is lost on the A-scan screen. Again, where the weld is pure, no back surface will be received until the sound has traversed the circumference providing a point of replacement approximates the locality of the probe. Should the waves which are proceeding through the wall of the tubing encounter flaws either partially or completely at right angles with the direction of the path at that point, then a definite flaw indication will be received. If the flaw is not perpendicular, then an indication will appear only if a point of reflection is within the hearing area of the probe. If the tube has been inspected previously and found free of flaws and flaws are noted after welding, then it follows that they lie in the weld area.

Case 5 -- When inspecting a tube of wall thickness in excess of 0.125 inch, similar problems exist as in thin-wall tubing. However, refraction conditions are such that pips may be obtained representing both the outer and inner surfaces of the tube, together with flaw indications which may be in the pips. The differences in scope picture, shown in Figure 57, are due entirely to the

FLAW DEPTH DETERMINATION WITH RANGE MARKERS

FIG. 52

FLAW DETERMINATION THROUGH
PARTIAL PENETRATION

FIG. 53

DEPTH DETERMINATION THROUGH TWO-DIRECTIONAL SCANNING

PART NO. 433

THE GIMMAL DOLLY WAS DESIGNED FOR ULTRASONIC TESTING WHERE THE USE OF THE IMMERSION TANK WAS IMPRACTICAL.

A WATER STREAM IS USED TO CONDUCT THE ULTRASOUND FROM THE CRYSTAL TO THE PART BEING INSPECTED. THE WHEELS ARE ADJUSTED SO THAT A FLAT SURFACE OR A PIPE AS SMALL AS SIX INCHES IN DIAMETER CAN BE READILY SCANNED.

THE GIMMAL DOLLY MAY BE USED WITH THE MODELS 424 OR 425 TESTING EQUIPMENT DESCRIBED ELSEWHERE.

GIMMAL DOLLY

FIG. 55

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SEAM WELDS IN THIN WALL TUBING

FIG. 56

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WELDS IN THICK WALL TUBES

FIG. 57

302 059

increased thickness of the material which tends to separate the back and front surface echoes. Flaws will appear at some point to the right of the surface echoes.

Case 6 -- The situation presented in Figure 58 illustrates the inspection of a weld in a heavy plate. The rough surface of the weld bead prevents inspection of the weld zone from a point directly above the weld bead. It is therefore necessary to enter the weld from an extreme angle such as 30 to 45 degrees from normal, thus permitting the ultrasonic waves to refract to a sufficiently parallel path within the material. A more acute angle with the part is not recommended since, in all probability, the entire sound wave will merely reflect from the surface and not enter the piece itself. This condition is not restrictive, however, since ultrasonic sound waves, entering a medium in which their velocity is greater, will change internal angles rapidly for small changes of external angles.

An example of this change can be shown mathematically by converting Snell's Law of Refraction in optics to the refraction of sound waves. This is possible because sound waves follow the same rules of refraction and reflection as sound waves, substituting the velocity of sound where the velocity of light presently exists.

Referring to Figure 59, Snell's Law of Refraction states that if radiation in one medium is incident upon the surface of another medium at an angle α , it will proceed into this medium at an angle β , between the normal to the surface and the direction of propagation. The ratio of the sines of the two angles is the relative index of refraction of the second medium against the first.

$$a. \quad n_{1-2} = \frac{\sin \alpha}{\sin \beta} = \frac{n_2}{n_1}$$

The relative index of refraction is equal to the quotient of the absolute indices of refraction of each medium. Since the velocity of sound (or light) is constant in a vacuum, the following relationship may be derived:

$$b. \quad \frac{\sin \alpha}{\sin \beta} = \frac{\frac{V}{V_2}}{\frac{V}{V_1}} = \frac{V_1}{V_2}$$

where V_1 and V_2 are the respective velocities in the two media.

In applying this formula (b) to immersed ultrasonic testing, it is well to note that the velocity of ultrasonic sound waves in water is less than one-third what it is in steel or aluminum. For the sake of simplification, a one-to-three ratio shall be used. Assuming an entry angle of 10° from the normal (angle α), a refraction angle of:

BAR OR PLATE WELDS

FIG. 58

REFRACTION

FIG. 59

TYPES OF WAVES

FIG. 60

$$\frac{\sin \alpha}{\sin \beta} = \frac{\sin 10^\circ}{x} = 1/3$$

$$x = 3 \sin 10^\circ = 3 (0.17365) = 0.52095$$

$$\sin \beta = 0.52095 \quad \beta = 31^\circ 23'$$

is found, which, it might be noted, is somewhat larger than three times the incident angle. This is generally true of all angles less than 15° . Also, at this point, for angles of incidence greater than 15° , no longitudinal energy at all will enter the piece.

When a longitudinal wave strikes a boundary between two media of different acoustic impedance at an angle other than normal (90°), the energy entering the material is transformed into shear and surface waves. The surface waves will be damped in short order by the water and will, in most cases, not affect the search crystal. Figure 60 illustrates the comparative motion of longitudinal, shear, and surface waves.

The shear waves are considerably slower than the longitudinal waves, but will produce the same indication on the screen as longitudinal waves. To produce shear waves it is necessary to tilt the search tube to some angle away from the normal, in the angular range between 15 and 33 degrees. A rather small and poorly defined echo is obtained from the front surface of the material. The flaw echoes, however, will appear strongly where vertical cracks or fissures exist. By moving the probe horizontally at the same angle, the distance between the front surface indication and the flaw echo will increase or decrease, showing that the distance to the flaw is relative to the location of the search tube. An approximation of the location can then be made.

Case 7 -- In the situation where the front surface is so rough or of such a nature that the sound is completely scattered (Figure 61), there will be little penetration achieved by the sound waves. An additional loss is experienced with the return echoes, which are further scattered by the under surface of the material. The recommended procedure would then be to smooth the surface by use of a disc grinder or belt sander just enough to allow normal reflection and penetration. Another solution would be to attack the problem through a smoother surface from some other angle. A low frequency should be used where roughness is extreme but not prohibitive.

Case 8 -- In the cases of laminated, brazed, welded, or otherwise bonded materials connected face to face, a good, uniform bond is necessary to receive satisfactory indication. When a good bond is present, clear readings of the normal front and back surface reflections as well as some indication of the location of the bond will be received.

EFFECTS OF ROUGH SURFACE

FIG. 61

302 064

Figure 62 illustrates this condition.

Where a poor bond is noted, it will normally indicate that there is a void present. The sound waves, unable to penetrate the void, will return a series of indications such as is shown in Figure 63. This will locate the bonding surface and the poor bond. The back echo will be lost entirely. The series of echoes is caused by reverberation within the top plate.

This method is extremely valuable in determining bond quality as well as laminar thickness. It should not be used on laminar layers less than 0.125 inch.

Case 9 -- In the situation where inspection is attempted on relatively porous materials, it is recommended that low frequencies be used. A clear and precise front surface reflection will be derived but the back surface will, in all probability, be absorbed or dissipated by the constant filtering of the pores. Either the reflection will be greatly reduced or completely missing. The clear pip of the front surface will probably be followed by a long series of "hash", so called because they are not necessarily indications of flaws but represent the porosity of the structure itself. If a flaw of worthwhile proportions is present, it normally will appear in larger size than the "hash", providing the sound penetrates satisfactorily to that depth. The disappearance or serious reduction of the back surface indicates that porosity is too high for acceptability.

Case 10 -- In the situations outlined above, definite techniques can be applied towards their solution. The majority of flaws located through ultrasonics will fall in one of these general categories. However, occasionally situations will arise which will apply to none of these. Under these conditions, the individual problem will draw on the ingenuity and experience of the operator for solution. At times, it may be necessary or desirable to obtain information or opinions from the manufacturer of the equipment or other well-qualified individuals versed in the field of ultrasonics.

GOOD BRAZE

FIG. 62

POOR BRAZE

FIG. 63

Penetration Characteristics

The penetration characteristics in immersion testing are considerably better than those noted in contact testing. In the first place, it is noteworthy that the surface and flaw echoes are sharper and more clearly defined than those noticed in contact testing. This makes it possible to read to a considerably thinner surface thickness blind spot.

The Electrocircuits Model 424 Immerscope has been, at various times, credited to accurate readability at a depth of one-tenth of an inch. This was made in the light of known facts, which, at the time, was the shallowest depth known to be readable. Since then, Rohr Aircraft has reported reading discontinuities as small as 0.005 inch in diameter at a depth of 0.060 inch. This, however, although backed by metallurgical sectioning, is to be considered as exceptional resolution and not a normally occurring condition.

However, diameters of this size are easily picked up by the A-scan. Of course, unless the machine has been calibrated to this size of defect, it is difficult to recognize the diameter on the screen. The Electrocircuits Company will only guarantee readability of flaws at a depth of 0.125 inch. This is the depth attainable even by the novice who is not too sure of his indications.

The new Sperry Model UW Reflectoscope claims a depth of 0.090 inch readability when coupled to the Simac Immersion equipment. The exact minimum size of defect readable is not known, but is, in all probability, comparable to the Model 424 in performance.

Much of the difference in the resolving power of immersion testing over contact testing lies in the new features included in the former. The higher frequencies used permit clearer penetration in some materials. Of course, lower frequencies still permit deeper penetration. Secondly, the immersion method gives surer, more consistent contact, and with the low viscosity of water, many of the surface voids are filled, permitting detection of deeper voids.

Once the initial surface of the part under inspection has been penetrated, the penetration characteristics of the material are similar to those of contact testing.

Accuracy

The accuracy of immersion testing results is slightly higher than that noted in contact testing. Here again, new circuitry makes the difference. The new sweep spread circuitry permits greater readability of proportion which is the largest factor in accuracy. Also, the peaks are more readily determined with high-speed circuitry. Methods of making measurements are identical to those previously discussed.

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Calibration

Calibration of immersion-type instruments are similar to those used in contact testing. At present, the UR Reflectoscope should be calibrated utilizing similar methods as described for contact testing. Hitt and/or Alcoa Blocks may be used in the calibration with settings similar to those outlined for the Immerscope below.

Calibration of the Electrocircuits Immerscope also applies to the setup for the actual testing. Below is the test and calibration procedure as outlined in the Immerscope Handbook:

1. Attach the manipulator carriage to the immersion tank and secure the search tube in position. Place one of the test specimens or test blocks in the tank, taking care to remove all surface bubbles from the surface, and lower the search tube directly above it until the crystal is totally immersed in the water and approximately two inches from the upper surface of the specimen.

Wipe the face of the crystal gently to remove air bubbles which may be trapped beneath it as well as excess grease or foreign material. Position the tube directly over the test specimen and check it for perpendicularity to the upper surface of the test material.

2. Turn on the power switch which is located in the lower left-hand side of the control panel (Figure 64, Item one). Allow approximately one minute time interval for the instrument to warm up before proceeding.
3. Turn the frequency selector switch, which is located in the lower center section of the control panel (Figure 64, Item two), to the frequency corresponding to the search crystal in use. For example, a five-megacycle crystal will require a setting on "5 MC". A green line should appear on the face of the cathode ray tube (Item 3). Where the incorrect frequency has been chosen, no indication echoes from the test block will appear.
4. The receiver gain control is located in the lower left-hand corner of the front panel (Item 4). This control is used to adjust the sensitivity of the flaw detector circuit. Make sure that the shaft locking lever (Item 5) is in the counter-clockwise position prior to any adjustments to the gain control. This lock lever is used to ensure that the sensitivity of the instrument is not accidentally changed. Now rotate the gain control dial to the full "ON" position, giving maximum sensitivity to flaws.

IMMERSCOPE - MODEL 424

If the search tube is pointed at the test block or material and is correctly adjusted, echoes from the metal should appear on the cathode tube screen. Absence of echoes at this point would indicate one of several adjustments necessary:

- (a) The frequency, Item 2, does not correspond to that of the crystal. In this case, adjust the dial to correspond.
 - (b) The segment of time being displayed on the screen does not include the area of the metal sample. In this case, adjust the time delay control, Item 6, as outlined below.
5. Rotate the time delay control, located at the lower right-hand corner of the front panel. When an Alcoa Test Block is under the crystal, the echoes on the screen should be adjusted to conform to Figure 65. Spacing between the echoes will depend upon the sweep magnification used. This magnification is adjusted by rotating the two upper dials, Items 7 & 8. The left-hand dial makes large changes in magnification while the right-hand dial makes fine changes.
 6. Changes of magnification control will normally require readjustment of the time delay control since the echoes may slide out of view. This control also enables the operator to examine a particular series of echoes once the magnification has been increased.
 7. Turn on the marker switch, Item 9, which will be found on the right center of the panel. With the marker switch on, a series of downward pips will appear on the screen to the right of the first upward pip. Since the horizontal green line actually represents time, these markers represent increments of time. The length of time between reflected echoes is thus used to calculate distance. By means of the small adjustment knobs, the markers may be set to indicate in inches. This is accomplished by the use of test blocks or other material at a section of known thickness. The space between the front and back surface echoes of the specimen as projected on the cathode screen represents the thickness of the test specimen. Using a specimen four inches thick, for example, the marker knob should be adjusted so that the fourth downward pip coincides with the back surface echo. The thickness of the test specimen as displayed on the screen is now divided into four equal segments, and the distance between the markers represents a distance equal to one inch. Since sound travels faster in some materials than in others, this is the only method presently in use to adjust the marker to fit the specimen. This adjustment should be made again before different materials are used.

INITIAL SETTING

FIG. 65

DEPTH AREA OF INTEREST (FINAL PRODUCT AREA)

FIG. 66

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8. Turn the flaw alarm switch which is located on the left center of the panel to the "ON" position, (Item 10). Lift the hatch door (Item 11) located in the right center of the panel below the marker switch and observe that there are three controls in the recess. These controls may be adjusted by means of a screw driver. These controls provide for the adjustment of the following flaw alarm variables:

- (a) Left-Hand Control -- Adjusts the distance beneath the surface that a flaw must lie before the alarm would sound off. This is especially useful in situations such as those outlined in Figure 66. In this case, only that portion of the material that will remain after machining is of interest to the operator.
- (b) Middle Control -- Adjusts the depth beyond which the flaw alarm will not operate. In effect, the control outlined in the above paragraph will locate a minimum depth before which the alarm will not operate and the middle control locates a maximum depth after which flaws located will not trip the alarm, (Figure 67).
- (c) Right-Hand Control -- Adjust the strength required of the echo signal from the flaw before the alarm will be initiated.

When the flaw alarm switch is turned to the "ON" position, a downward directed notch will appear near the front and back echoes on the screen Figure 68. This notch is provided to show the operator the area on the screen where the flaws will be monitored. Position and notch width are controlled by the above adjusting screws.

9. A plug connection is provided at the rear of the instrument for feeding the flaw signal to external lights or bells.
10. The sensitivity time control is a screwdriver-adjusted control located on the right side of the cabinet. It is used to provide compensating amplification of the later signals which become weaker in intensity as the sound penetrates further into the material. For example, if a sample consists of one or more forgings one foot thick and it is desirable that the alarm operate when triggered by any flaw over 1/16 of an inch in diameter, it is necessary that the echo from such a flaw be detected with equal regularity whether the flaw is located one inch or eleven inches below the upper surface of the material. By properly setting this sensitivity time control, the necessary height of flaw echo is obtained regardless of the depth of flaw. This must be adjusted by use of a test block in which a given

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FLAW ALARM AREA SETTING

FIG. 67

"NO SIGNAL" AREAS BY PRE-SETTING

FIG. 68

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size of flaw is built-in accurately at minimum and maximum depth.

11. The Immerscope is thus adjusted in all respects to give indications of the size and location of flaws in a given material. The machine must be calibrated periodically even when the same material is used throughout. This assures the operator that his findings are correct and that no accident change has taken place. It is especially important to stress the necessity for recalibration where different materials are going to be used prior to the application to the new materials.

Test Blocks

Test blocks used in immersion testing are the same as those used in contact testing. Hitt Blocks in steel or aluminum and Alcoa Blocks may be purchased. Special blocks may be fabricated for special material.

Limitations

Perhaps one of the most outstanding limitation in using immersion testing is that facing users of any ultrasonic method as an inspection medium. This limitation is the degree of acceptance by the metals industry of results determined through the use of ultrasonics.

It is difficult to state an exact degree to which results obtained through ultrasonic immersion testing are presently accepted in industry. With the passage of time, as the usefulness of ultrasonics is proven, the resistance to acceptance is fading. It is hoped, as technique and resolution are improved, that ultrasonics will eventually reach general acceptance.

To date, the organizations most directly affected by ultrasonic inspection results have been the mills. As a result, the hardest core resisting the acceptance of ultrasonic results is centered in this industry. However, the Aluminum Company of America has been investing in considerable research at their New Kensington, Pennsylvania, plant to derive satisfactory areas of ultrasonic application in their products. Although the extent of their usage of immersion equipment is not too great, it has still shown considerable improvement over other mills on at least one product. One particularly critical part on which considerable study has been expended showed that the Alcoa Blocks experienced approximately a ten per cent rejection rate, Reynolds Aluminum approximately thirty per cent, and Kaiser Aluminum considerably above either of these. These figures, it must be remembered, apply only to the one critical part under discussion, and do not imply that this is a general condition on all incoming materials. Such over-all figures are not available. However, it does indicate the additional strain placed on the mills from a quality-metal-lurgical viewpoint by ultrasonic inspection, explaining to a degree the resentment, if it may be called such, to the new medium. The increased

rejection rate tends to rise sharply as more and more quantity users employ ultrasonics and tighten requirements as a result of their findings. There is often a tendency among engineering groups to overemphasize their requirements in their work to overcome the unknown factors in the various materials.

Many of the present users of ultrasonics have been working towards widespread recognition for several years now. Of course, they are comprised mainly of major fabrication plants using the mill products. They are thoroughly sold on the usefulness of ultrasonics, which is bolstered by the increased interest in and demand for ultrasonic equipment.

For example, Rohr Aircraft and Convair are rejecting materials on the basis of metallurgical cross sectioning in areas originally noted as defective in ultrasonic inspection. The metallurgical aspect is necessary since their contracts to material suppliers do not specify ultrasonic standards or requirements. Such inclusion, they claim, would raise the cost of materials beyond reason.

Other organizations requiring ultrasonic standards may reject outright on ultrasonic results. Rohr and Convair, however, have found that their word in the rejection of materials is sufficient, since other markets can still be found for the rejected materials where the requirements are not so stringent.

Another major limitation in the use of immersion testing is the newness of the field itself. So much depends on the skill and integrity of the operator, and there are so few skilled operators in the field. A major portion of the knowledge in ultrasonics still lies in the future studies. Much of what is known cannot be clearly put down on paper, and demands individual instruction.

For a broad application of the instruments to many different materials, a great deal of destructive testing is necessary. However, the majority of the destructive testing is necessary to train the operator in recognizing precisely what it is that he is looking at when a flaw appears in either the A-scan or B-scan. It has been found that considerably less destructive testing is needed to train an operator with B-scan included in the equipment than without B-scan. The reason for this is that the B-scan so pictures the defect that it is relatively simple for the operator to realize shape, size, and direction of the defect. An extensive program would not be necessary on each item of the production line. The various external shapes do not require studies in themselves. Experience gained on one shape is equally valuable for all shapes. Studies into keyways, fillets, and rounds hold good on any part where these configurations appear. The length of destructive correlation depends on the degree of rapidity that the operator gains the necessary experience.

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Uses

Since little work has been done in the field of finished machine product testing by immersed ultrasonic methods, there is little known of the uses in this area. While it is generally recognized that measurements in areas not perpendicular to the probe are workable, considerable confusion exists as to whether keyways and sharp machined corners will give satisfactory information. Criticism of finished part inspection is tempered, however, by the excellent work accomplished by William Hitt of Douglas Aircraft, Santa Monica, and the Ultrasonic Testing and Research Laboratory. Mr. Hitt has found considerable success in certain methods of inspection into radii and corners, with findings borne out by subsequent destructive tests. The technique, however, can only be developed through trial and error. Consequently, Table I is based on studies made on incoming raw materials with the Electrocircuits Immerscope. The table may also be readily applied to most finished machine items.

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TABLE I

<u>MATERIAL</u>	<u>APPLICATION</u>	<u>METHOD</u>	<u>REMARKS</u>
Sheet Metal 0.001 to 3/8"	Good	Shadow	The setup is made with the sample placed on sheet or plate stock of considerably thicker cross section. If a flaw occurs in the sheet metal, it will reduce the strength of echo received from the distant object.
Sheet Metal 3/8 Several Feet	Excellent	Direct	This method will detect any flaw lying 1/8 inch or deeper in aluminum sheet or 1/4 inch or deeper in most types of steel alloy sheets. At these depths, indications can be read without difficulty by any operator. Shallower depths can be read by more experienced operators.
Rods, Shafts Bar Stock	Excellent	Direct	The equipment can inspect aluminum rods, shafts, and bar stock up to several feet thick or long which may be inspected either across the diameter or along the longitudinal axis. This method will reveal defects to a depth no shallower than 1/8 inch to the less experienced operator.
Ingot Aluminum	Fair	Direct	This method is excellent for use with ingot relatively free of gas content. Where a low gas content is present, inspection can be made at 5 MC. As gas content increases, lower frequencies should be utilized. Use of B-scan in this operation greatly improves the ability to interpret the data indicated by the A-scan and also speeds up the inspection process.
Ingot Steel	Poor	Direct	This method is poor for use with ingot steel due to the grain structure before rolling. High porosity will also affect results. Here, again the value of B-scan in obtaining the profile trace of the defects cannot be underestimated. The use of 2.25 MC or lower is required.

TABLE I
(Continued)

<u>MATERIAL</u>	<u>APPLICATION</u>	<u>METHOD</u>	<u>REMARKS</u>
Cast Iron	Poor	Direct	The same situation exists on cast iron as it does on cast steel. Much of the resolution depends on porosity and grain structure. However, as a rule, the immersion equipment can inspect about two feet into most castings using 2.25 MC and about one foot in depth at 5 MC.
Extrusions	Excellent	Direct	Application to extrusions is excellent, particularly to aluminum extrusions. This application allows detection of flaws to within 1/8 inch of the surface. Flaws lying several feet from the surface are easily seen.
Forgings 4140, 4130, 1625, S-816, 19-9DL, etc.	Excellent	Direct	The use of 5 MC in this application will penetrate several feet, and is capable of revealing flaws within 1/4 inch of the surface. Where the metal is pure, flaws within 30 feet along the length of shafts or beams become visible.
Castings	Fair	Direct	A frequency of 15 MC may often be applied in the study of castings providing the casting is relatively free from porosity, inclusions, and sand pockets. Some adjustment will be necessary to the equipment as the study progresses until a clear picture is obtained.
Welding	Fair	Angle	For good results in studying welds it is advisable not to attack the weld directly unless the weld is parallel to one of the flat sides of the part (Figure 69). In all other cases the search unit must be directed at an angle to the surface adjacent to the weldment so as to cause shear mode ultrasonic waves to cross into the weld material.

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(A) DIRECT SIGHT PERMISSABLE

(B) ANGLE SHOT REQUIRED

ULTRASONIC APPLICATION TO WELDING

FIG. 69

- A. MAIN WATER BANG
- B. FRONT SURFACE ECHO
- C. BACK SURFACE ECHO (NOT NEEDED)

SHADOW IMMERSION METHOD

FIG. 70

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THE SHADOW IMMERSION METHOD

Discussion

Since shadow immersion is merely a deviation of the standard immersion pulse-echo method, a very brief method of the technique will be outlined here. Basically, the equipment and the techniques used in this method are the same as those used in immersed pulse echo. However, due to attenuation factors and other power losses, the shadow method is only useful in material thicknesses of $3/8$ inch or less.

Technique

The object of this technique is to measure the soundness of a piece of sheet material which is $3/8$ inch thick or less. In this method, the test piece is placed over a thicker sheet of stock (Figure 70). The crystal is then aimed through the actual test piece and records on the screen the normal front and back surface of the back plate. In checking the test piece, however, only the front echo of the bottom piece is of interest.

For this reason, the front echo of this piece should be centered on the screen and preset to a desired known height or scribe mark while a flaw-free piece the same thickness as the test sheet is in position on the back plate (Figure 71). Fluctuation of this echo after the actual test piece is in position will indicate the presence of flaws in the search stock. Flaws to the right of the initial echo should be ignored, since they are merely indications of flaws in the back plate.

This method should be used only after a diligent study program has been conducted by the operator and he has become thoroughly trained to determine true flaws from false indications due to uneven mating of the stock.

Limitations

Use of the shadow immersion method should be restricted to extremely thin pieces between 0.001 to $3/8$ inch thick, and only when resonant equipment is not available.

Uses

The shadow immersion method is useful in tank inspection of thin sheet stock for continuity. It may also be used in the detection of defections in thin laminar bonds.

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A. FLAW FREE TEST BLOCK

B. FLAW IN SAMPLE SHEET

A - MAIN WATER BANG
 B - FRONT FACE ECHO
 C - FLAW INDICATION

FIG. 71

THE RESONANCE METHOD

Discussion

Instead of applying a pulse of energy to the crystal, which is the method of energizing the pulse-echo system, the energy is transmitted in a continuous stream in the resonance system. It is similar to the pulse-echo system only in the fact that the crystal is sent into vibration. The major differences between the two systems is that, in the resonance case, the vibration is transmitted into the piece, and resultant sound energy is merely a medium by which the vibration is transmitted, but otherwise is of little consequence. The crystal is vibrated and the vibrations pass into the material through a contact similar to that used in contact pulse-echo testing. The frequency of the vibration is controlled by the electronic circuitry coupled to the crystal. Providing the frequency range of the instrument is compatible to the test material, the test piece is then brought to a resonant frequency. A resonant frequency is a frequency which is natural to the structure of the material, and it varies somewhat from piece to piece and material to material. However, the range of application is normally wide enough to compensate for variations in thickness and resistance to vibration. Since the resonant frequency of a given material is determined by the velocity of sound in that material and the thickness of the material itself, the thickness of the piece can be determined quite accurately if sound velocity is known. Figure 72 gives a simple circuit diagram of an early hand-tuned model of a resonant system using a meter to indicate when the resonant frequency has been reached. This is accomplished by watching the meter for an increase in current, indicating that resonance has been reached. A simple oscillator feeds the crystal which is coupled to the work with a thin film of oil.

The resonant system requires that both surfaces be relatively smooth and nearly parallel.

Crystal

The crystal used in resonance testing is similar to that used in the pulse-echo method. The application is similar to the pulse-echo contact method.

Coupling

The coupling is accomplished through the use of a film of light oil. Again, the oil used in contact pulse-echo coupling is ideal; either a light machine oil, mineral oil, or other inexpensive material of similar viscosity.

ELEMENTRY CIRCUIT DIAGRAM OF THE RESONANT SYSTEM

FIG. 72

CONTACT TRANSMISSION SIMPLIFIED

FIG. 73

Uses

The resonance system is useful in the sorting of materials according to thickness. It may also be used to detect laminar faults or the quality of bonding.

The normal range of application is for thicknesses between 0.015 to about 0.400 inch. However, this thickness may be increased by the use of harmonics on the oscilloscope screen. Direct thickness measurement is made.

Limitations

The resonance system will not pick up defects of small magnitude. Defects smaller than twenty-five per cent of the crystal area are completely overlooked, and those smaller than seventy-five per cent are difficult to detect.

FREQUENCY MODULATION

Discussion

A recent newcomer in the ultrasonic inspection field is a system employing frequency modulation equipment in a submersion method. This system operates similarly to an aircraft altimeter. Both the frequency modulation and pulse-echo submersion methods have been used in automatic devices for flaw detection and flaw plotting in parts with complicated shapes.

CONTACT TRANSMISSION

Discussion

The Ultrasonic Transmission method is identical in all respects to the pulse-echo method except for the fact that the receiving and transmission is accomplished through the use of two crystals. This means that the transmission is continuous and there is no "listening" period involved in the crystal. A simple diagram of transmission equipment is provided in Figure 73.

Crystal

The same crystal used in the pulse-echo system may be used here. However, it must be remembered that two such crystals are necessary.

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Uses

The transmission method may be used in most applications where the pulse-echo method is usable.

Limitations

The limitations of the transmission system, both immersion or contact, is that a master control is required to keep the two crystals parallel. This requires a great deal of handling equipment and, as indicated in Figure 74, special jigs to hold and turn the work. This system is too cumbersome and expensive for the amount of good derived to be useful in Sandia application.

IMMERSION TRANSMISSION

The limitations of this means of transmission are the same as those for contact transmission. This system should not be used due to the high cost to benefit ratio.

HAROLD C. PSILLAS - 5511-2

Case No. 605.01
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BLOCK DIAGRAM OF THE TRANSMISSION SYSTEM

FIG. 74

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