ULTRASONIC NONDESTRUCTIVE TESTING

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DEPARTMENT OF TRANSPORTATION
Federal Aviation Administration

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ACKNOWLEDGMENTS

We wish to thank the Budd company, Krautkramer Ultrasonics, Inc., and Sperry Products Division Automation Industries, Inc.; manufacturers of ultrasonic nondestructive testing equipment for their assistance in providing illustrations and information for this advisory circular.

Reference to specific equipment is for the instruction of Federal Aviation Administration personnel only, and does not constitute a recommendation or endorsement of such equipment by the FAA.

The units described herein are typical of the equipment being used by the aviation industry today. There are many other manufacturers of ultrasonic nondestructive testing equipment.

ULTRASONIC NONDESTRUCTIVE TESTING

INTRODUCTION

The use of sound to determine the internal quality of an item is not new. All of us have thumped a watermelon to judge by ear its degree of internal ripeness. The sword maker of Toledo listened to the ring of his Damascan blade to determine its internal quality. Railroad wheels were tapped with a hammer in an effort to locate hidden defects. Doctor's stethoscopes and sensitive microphones, in conjunction with a high-pitched whistle were used in attempting to judge by ear the internal quality or freedom from defects of metals and other materials by audible sound.

In the latter part of the 19th century, a German named Koenig, with the aid of a small-pronged tuning fork, was able to generate vibrations of the order of 90 kilocycles. In 1900, Edelmann, using a controlled air stream in a device called the Galton whistle, was able to produce vibrations of 100 kilocycles per second.

Between 1900 and 1930 several other methods of producing ultrasonic vibrations were tried. These early methods include a spark-gap system, a mechanical generator, and a gas-current generator. Although none of these schemes were of any lasting value, each served its purpose in advancing the art. During this same period, the two methods for generating high-frequency sound, which are generally used today, were developed—they are the magnetostrictive and the piezoelectric systems. The first practical success of ultrasonics was the application of piezoelectric-generated waves to detect submarines during World War I.

During the 1930's, O. Muhlhauser, A. Trost and R. Pohlman of Germany and S. Sokoloff of Russia investigated various continuous-wave schemes in which the ultrasonic vibrations were produced and transmitted without interruption (pulsing) in the time dimension, or change in their frequency or amplitude. In 1940, Floyd A. Firestone, of the University of Michigan, invented the reflectoscope method. Using longitudinal (compressional) mode waves, he was able to determine the depth and extent of defects from only one side of the piece being tested.

From this period on, new techniques and improvements increased the science of ultrasonic nondestructive testing to its present level of preprogrammed, high-speed automated production line testing systems.

Basic components of an ultrasonic flaw detector consist of:

1. A power supply to produce the various required voltages.
2. The rate generator or timer, whose function it is to start and synchronize all other functions.
3. The pulser, which generates a high-voltage, short-duration spike to "shock" the crystal into resonant vibration.
4. The transducer (crystal) which transmits a high-frequency sound wave into the test piece, receives the reflected echo and converts it into an electrical impulse.
5. The amplifier or receiver, to amplify and properly prepare the echo signal for display.
6. The sweep generator, which starts to trace a line horizontally across the cathode-ray tube screen at the same time the pulse "shocks" the transducer into action.
7. The marker generator, which produces time marks, such as square waves to be presented simultaneously with the horizontal sweep to aid in depth measurement.
8. The cathode-ray tube which presents a picture of the echo signals.

Ultrasonics is a fast, reliable nondestructive testing method which employs electronically-produced, high-frequency sound waves that will penetrate metals, liquids, and many other materials at speeds of several thousand feet per second. Because ultrasonic techniques are basically mechanical phenomena, they are particularly adaptable to the determination of structural integrity of engineering materials. Their principle applications consist of:

1. Flaw detection.
2. Thickness measurement.
3. Determination of elastic moduli.
4. Study of metallurgical structure.
5. Evaluation of the influence of processing variables on the specimen.

The desirable features of ultrasonic tests include:

1. Versatility, access to only one surface of the specimen is needed and the test equipment may be taken to the work.
2. Fast response, permitting rapid and automated inspection.
3. Accuracy in the measurement of flaw position and estimation of flaw size.
4. Great penetrating power, allowing examination of extremely thick sections.
5. High sensitivity permitting detection of minute defects.

The following are a few applications, which indicate the capabilities of ultrasonic testing as it is practiced today. Ultrasonic techniques are used to detect laps, seams, laminations, inclusions, rolling cracks, and other defects in steel plates ¼″ to about 12″ thick. Discontinuities as small as 0.5% of the plate thickness are detectable as are laminations down to less than 0.00002″ thick. Ultrasonics are used to locate porosity, cupping, pipe, internal ruptures, and nonmetallic inclusions in bar stock and ingots of various sizes up to 48″ in diameter. Ultrasonic tests locate cracks, blow holes, insufficient penetration, lack of fusion, and other discontinuities in welds. Ultrasonics are used to evaluate bond quality in brazed joints and honeycomb assemblies. Ultrasonics are used to inspect forgings such as turbine shafts and rotors.

There are many factors which limit the application of ultrasonic testing, among the most important are sensitivity, resolution, and noise discrimination. Sensitivity is the ability of the instrument to detect the small amount of energy reflected from a discontinuity. Resolution is the ability of the instrumentation to detect flaws lying close to the test surface or to separate and distinguish the indications from several defects occurring close together in the specimen. Noise discrimination is the capacity of the instrumentation for differentiating between the signals from defects and the unwanted noise of either electrical or acoustical nature.

These variables in turn are affected by others, such as frequency and pulse energy. For example, when frequency is increased, the sensitivity increases. With the increase in sensitivity, smaller inhomogeneties within the material will become detectable; this will increase the noise level thus hindering signal discrimination. With an increase in pulse energy, material noise will increase and resolution will decrease.

In addition, the geometry and condition of the test material may limit the application of ultrasonic testing. For example, size, contour, complexity, defect orientation, and undesirable internal structure such as grain size, porosity, inclusion content, and fine dispersed precipitants.

Problems concerning the couplants, surface roughness, and scanning also limit applications for ultrasonic testing.

Due to the many conditions which can and do restrict the application of ultrasonics, a successful inspection cannot be expected unless there is:

1. Ultrasonic testing equipment suitable for the specific application.
2. Capable operators.
3. A clear definition of the test problem.
4. Adequate reference standards.
5. Practical test specifications.

6. Realistic acceptance criteria.
7. Detailed test records.
8. Frequent inspection of the equipment.

Ultrasonic testing effectively employs physical phenomena to increase man's physical senses. To understand how inaudible sound is used to reveal certain conditions which are not perceptible to the normal senses, it is first necessary to know how ultrasound is transmitted and received.

TRANSDUCERS (search units, probes, crystals)

MAGNETOSTRICTIVE EFFECT:

In 1847 Joule discovered that a metal expanded and contracted under the influence of a changing magnetic field. He called this effect magnetostrictive.

The basic physical principles of this effect are such that when a ferromagnetic material, such as a bar of iron, is surrounded by a coil and a current is passed through the coil the length of the bar changes, creating compression (mechanical) waves.

This method of generating ultrasonic waves has certain disadvantages such as sensitivity to temperature variations, limited frequency range, and lack of tuning discrimination which has restricted its use for nondestructive testing purposes. However, recent development work indicates these disadvantages may be overcome when the ultrasonic waves are generated by means of the magnetostrictive effect in the test piece itself and an oscillation is not relied on.

Krautkramer Ultrasonics, Inc. produces an ultrasonic flaw detector called the "FERROTRON" (see Figs. 1 and 2). The manufacturer describes the advantages of this new instrument as follows:

"There is no need of a transmission medium (coupling fluid) since the generation of ultrasonic waves is achieved by means of the magnetostrictive effect in the test piece. The elimination of the coupling liquid offers the possibility to ultrasonically test hot material, to 1,000°F. in steel; freedom from coupling problems encountered on rough surfaces and pieces of small dimension; freedom of false indications from drops or ridges of couplant. The advantage of pulse-echo as well as the through-transmission methods are fully maintained. The sound waves can be aimed and concentrated. The generation of compressional, shear, and surface waves is also possible."

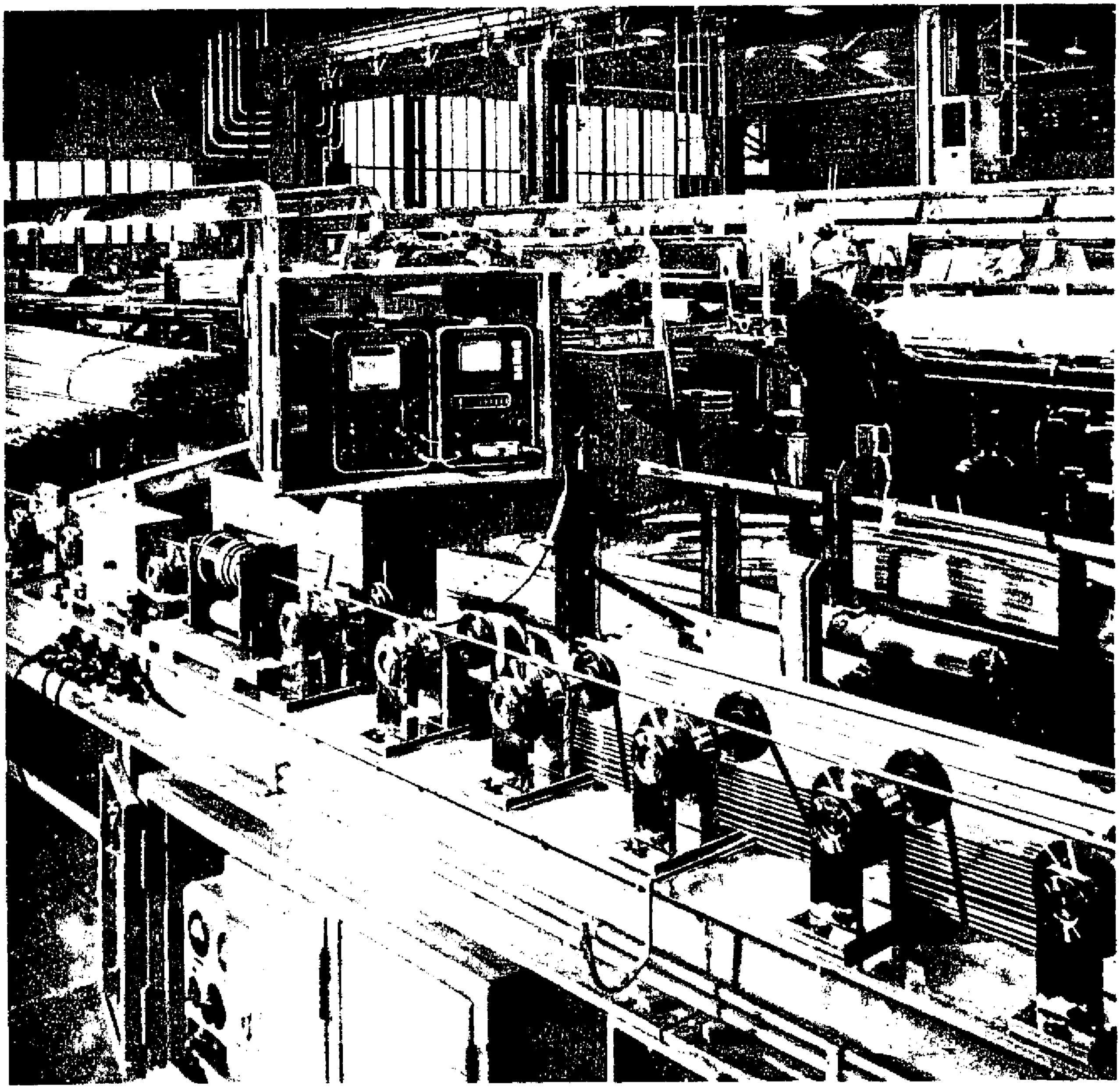
No attempt is made in this digest to discuss the technical details of generating ultrasound by means of the magnetostrictive effect since magnetostrictive transducers, at present, are most often used in high-power applications such as ultrasonic cleaning, welding, drilling, machining, etc. Ultrasonic nondestructive testing, as it is practiced today, almost exclusively uses the piezoelectric effect to generate ultrasonic vibrations.

PIEZOELECTRIC EFFECT:

The Curie brothers in 1880 found that crystals of certain minerals or salts, when subjected to an alternating electric charge, expanded and contracted under the influence of these charges. Conversely, it was found that these materials when subject to alternating compression and tension, set upon their faces alternating electric charges (see Fig. 3). This was named the piezoelectric effect.

The heart of an ultrasonic testing system is this method of transforming electrical energy into mechanical vibrations, and transforming the mechanical vibrations back into electrical energy.

Generation of the ultrasonic pulse is usually accomplished by producing a radio-frequency wave train of the desired frequency at a precise time and converting this into vibrations by means of piezoelectric transducers. Some ultrasonic instruments do not use a radio-frequency wave train, but instead, use a shock pulse and allow the search unit to select the frequency of operation.



FEATURES:

Frequency Range 0.1–2.5 mc. Dry coupling to ferromagnetic materials. Contactless testing, possible to test hot materials, to 1000°F, in steel. Testing speeds up to 1000 feet per minute. Flaw distinction of longitudinal cracks deeper than 0.001". Facility for sorting, according to flaw depths. Automation suitable for testing bars and wires, from 0.160" to 0.560" in diameter.

FIGURE 1. Ultrasonic flaw detector.

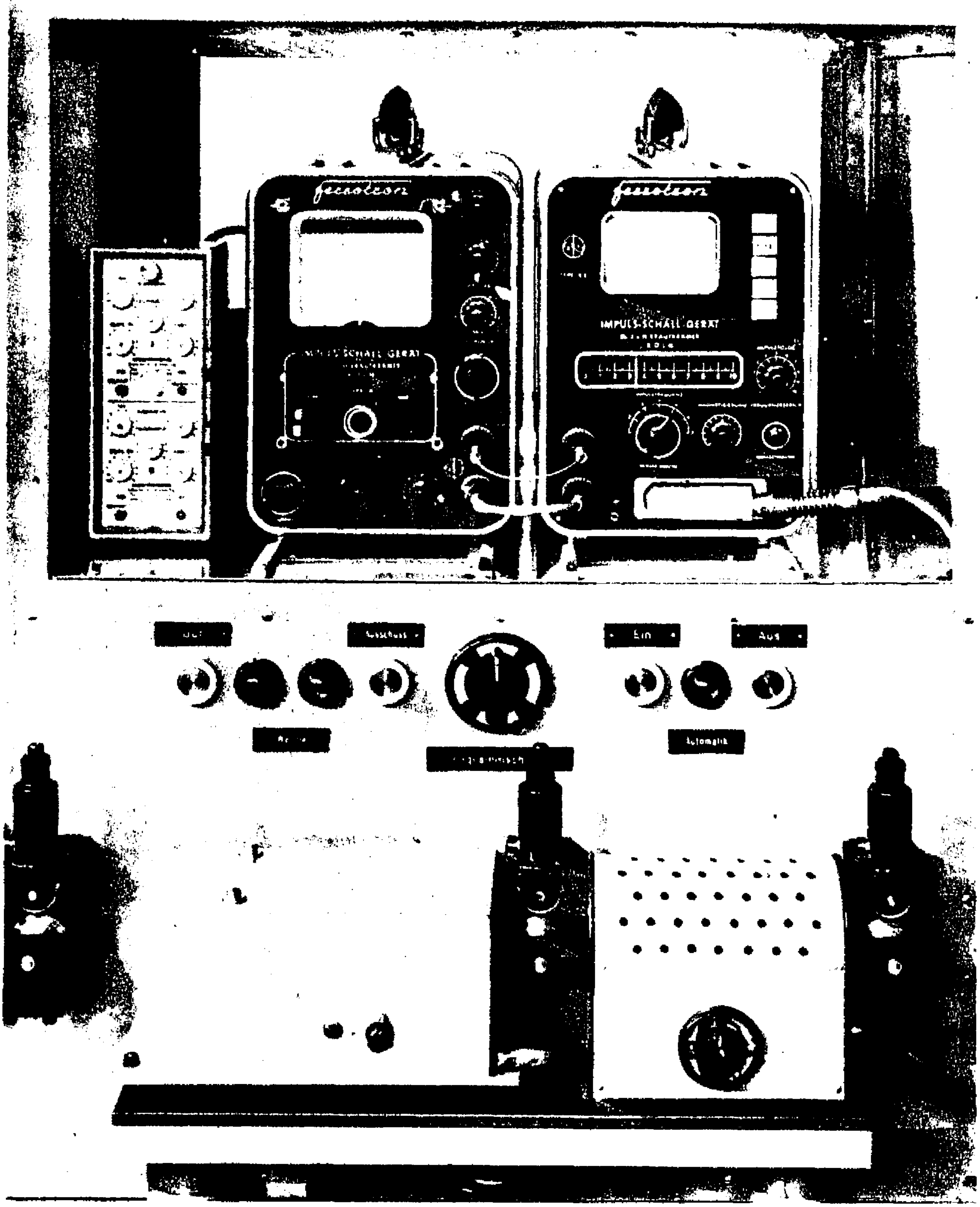


FIGURE 2. Ultrasonic flaw detector (close-up).

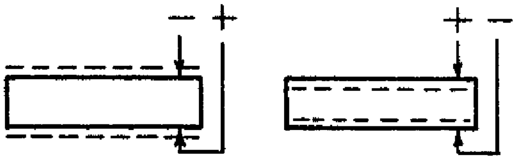


FIGURE 3. Generation of ultrasonic vibrations.

The three most common transducer materials used in the manufacture of ultrasonic search units are natural quartz crystals, lithium sulfate monohydrate crystals, and polarized crystalline ceramics, such as fired barium titanate or lead zirconate titanate.

Quartz—Principal advantages are: electrical and thermal stability, insolubility in most liquids, high mechanical strength, wear resistance, excellent uniformity and resistance to ageing. A limitation of quartz is its comparatively low electromechanical conversion efficiency.

Lithium Sulfate—Principal advantages are: ease of obtaining optimum acoustic damping for best resolution, intermediate conversion efficiency, and negligible mode interaction. Use is restricted to temperatures below 165°F., and above 32°F.

Polarized Ceramics—Principal advantages are: high conversion efficiency which yields high search unit sensitivity. Because of lower mechanical strength and relatively high electrical capacitance, their use is generally restricted to frequencies below 15 megacycles (mc). Another limitation is some interaction between various modes of vibration.

In order for a crystal to utilize its piezoelectric characteristics, it is placed in a circuit much like a condenser. That is, both faces are coated with a conducting material with no contact between the two faces (see Fig. 4). Coatings for crystals may be of any conducting material such as aluminum, silver, gold, or chromium. However, coatings are difficult to deposit on lithium sulphate crystals so thin metallic foils are often cemented to the crystal.

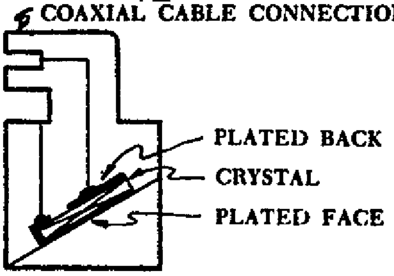


FIGURE 4. Angle-beam search unit.

TRANSDUCER TYPES:

The search unit consists of a shell for mechanical protection, a means to conveniently handle or mount the unit for use, the transducer element, electrical connections, and a backing material to dampen the backward directed energy that is transmitted by the crystal (see Fig. 5).

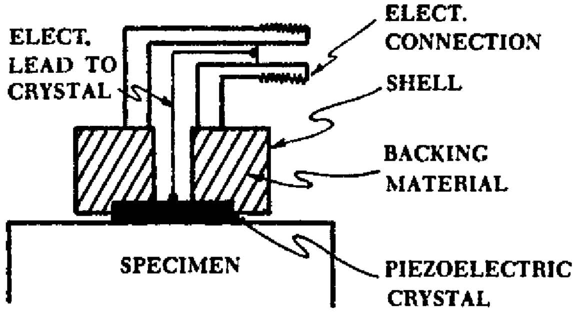


FIGURE 5. Diagram of an ultrasonic search unit.

To assure optimum performance in all types of ultrasonic inspections, the transducers are available in a wide variety of configurations and sizes which includes:

X—Cut crystals for longitudinal-wave generation (see Fig. 6)

Y—Cut crystals for shear-wave generation (see Fig. 6)

Dual crystals with common holder

Mosaics—three or more crystals

High frequency, 50 mc. or more

Alternate crystal materials

Sandwich and tandem arrangements

Curved crystals to fit the specimen

Wheel search units

Focused search units

High-temperature search units (for measuring wall-thickness at temperatures up to 1,100°F.)

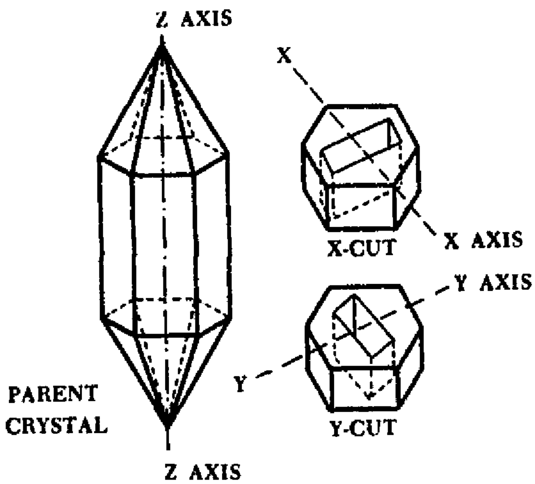


FIGURE 6. Natural quartz crystal (X & Y cut).

Transducers are available that are smaller than 1/8″ diameter and larger than 1″ × 4″ (see Figs. 7 and 8). However, for most ultrasonic testing, standard diameters of 3/8″, 1/2″, 3/4″, and 1.0″ are used.

The various types of search units used in ultrasonic testing fall roughly into two major categories – contact and immersion. The contact group includes straight-beam search units which transmit longitudinal waves into the material perpendicular to the test surface, and angle-beam search units which transmit sound waves into the material at an angle to the entrant surface. Search units in this group are used in direct contact with the material with only a thin liquid film for couplant. The immersion group includes all search units which transmit sound into the specimen through a water path or column. The immersion search unit is generally of waterproof construction.

TRANSDUCER GROUPS:

There are three general groups of transmitter-receiver search units:

1. Common Transmitter-Receiver (T-R).

These search units employ a single crystal and have common connections to the transmitter and receiver amplifier units (see Fig. 9).

Since the search unit acts as both transmitter and receiver, it transmits a pulse of 1 to 4 microseconds duration; then acts as a receiver for a period up to several thousand microseconds. This cycle of transmitting and receiving is repeated at a rate of 50 to 5,000 times per second, or higher if required for high-speed automatic scanning.

2. Combined Transmitter-Receiver (T-R).

These search units have two transducers mounted on a single head and insulated acoustically from each other. One transducer is connected to the pulser and the other is connected to the amplifier. The combined T-R search unit is used for testing close to the entry surface and for thickness measurements from .040″ to 2.0″ when the opposite side is rough or corroded. The transmitting search unit projects a beam of vibrations into the material; the vibrations travel through the material and are reflected back to the receiving search unit from any discontinuities or from the opposite boundary if parallel to the entrant surface (see Fig. 10).

3. Separate Transmitter-Receiver (T-R) Search Units.

Two heads are employed having separate electrical connections to the transmitter and the receiving units. One head is used as the transmitting unit while the other head is the receiving unit (see Fig. 11).

Materials which are course grained tend to scatter the ultrasonic sound beam; these materials can be effectively inspected using separate T-R search units that are mounted on individual wedges of a suitable elastic solid. When separate wedges are used, the angle of incidence may be varied according to the section thickness to be examined.

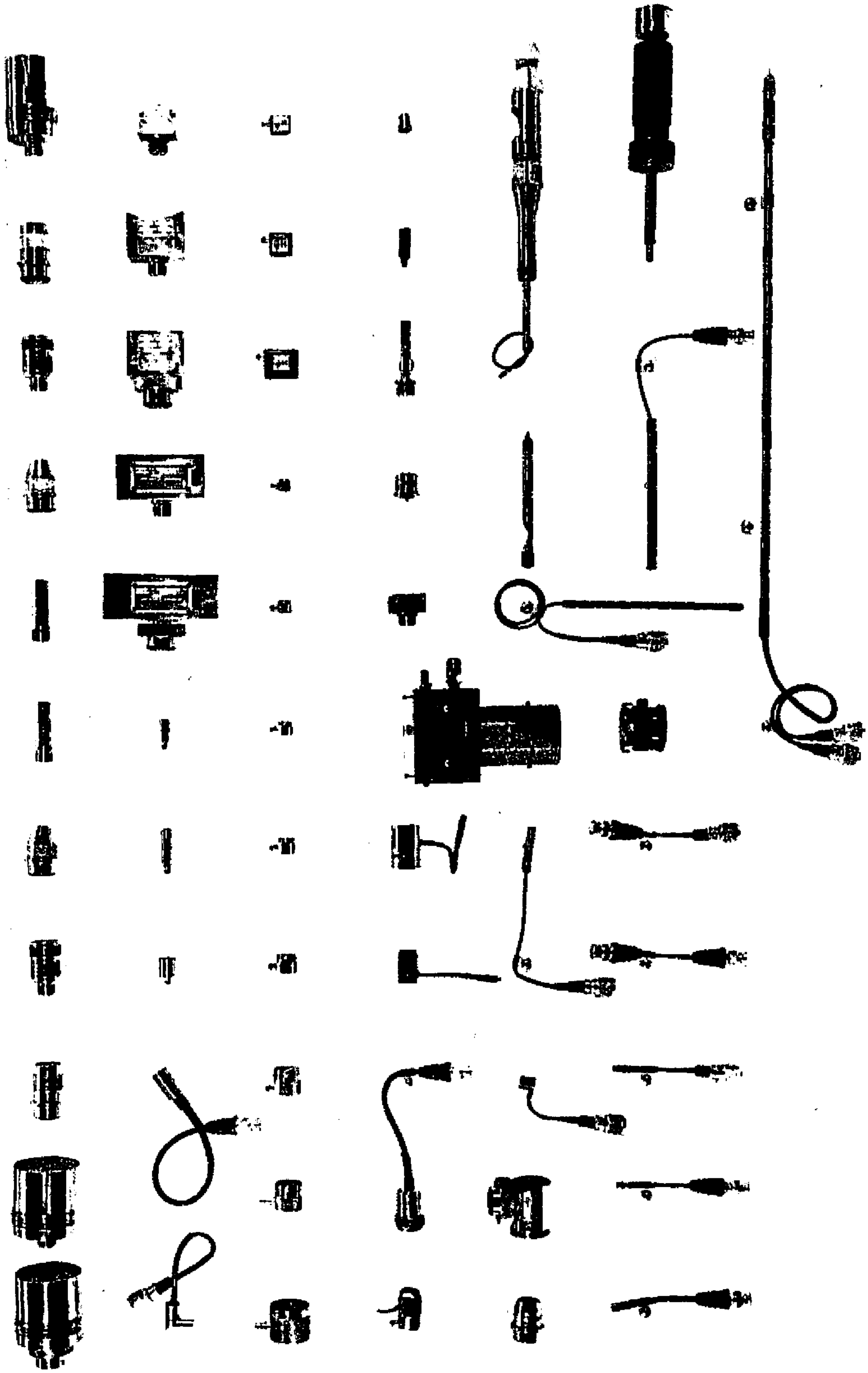


FIGURE 7a. Various search units.

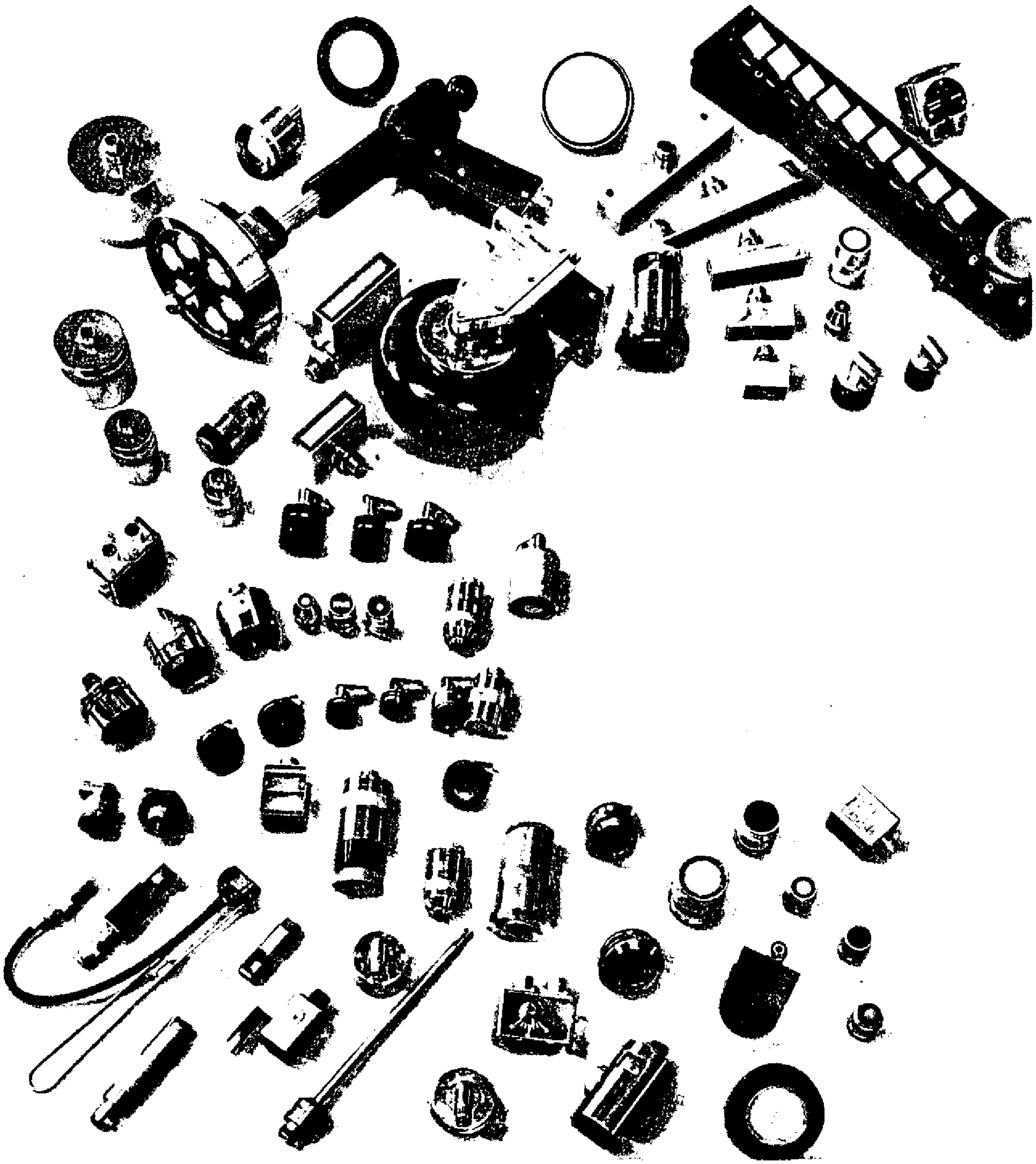


FIGURE 7b. Various search units.

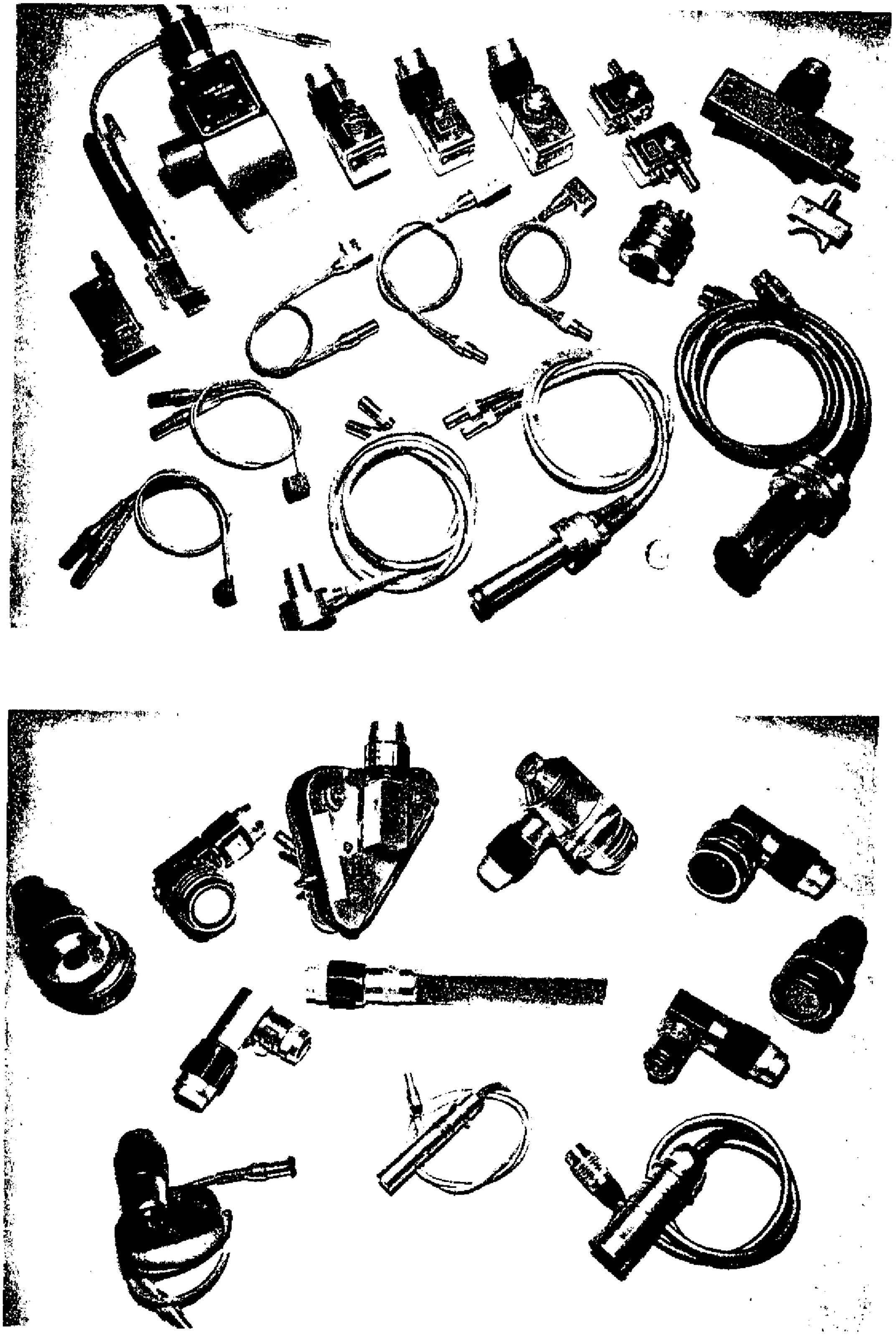


FIGURE 8. Miscellaneous search units.

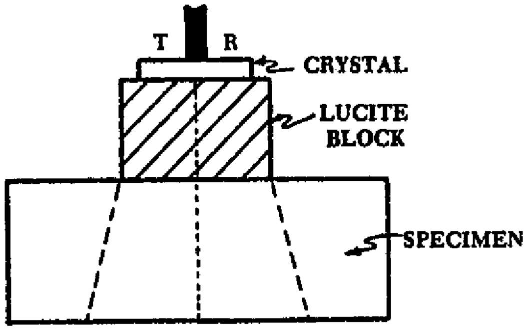


FIGURE 9. Common transmitter-receiver search unit.

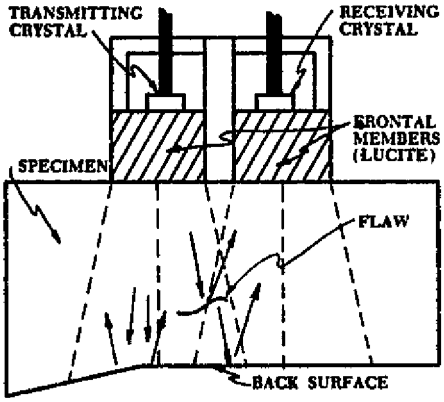


FIGURE 10. Combined transmitter-receiver search unit.

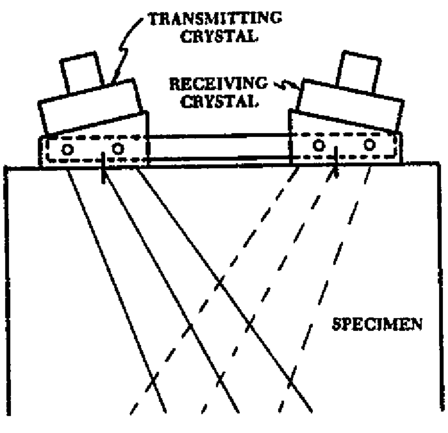


FIGURE 11. Separate transmitter-receiver search unit.

WAVE PROPAGATION

Ultrasonic waves can be propagated to some extent in any elastic material. This propagation, or traveling, of waves occurs as a displacement of the successive elements of the material. If one part of a solid is distributed or displaced in some manner, molecules in other parts of the solid will be affected, but not instantaneously. As successive molecules in the medium are displaced, the disturbance is propagated away from its point of origin (see Fig. 12). Since the lattice structure of all materials is elastic, a restoring force exists which tends to return each molecule to its original position. Because of inertia, these particles will tend to oscillate about their original undisturbed position until they come to rest. This molecule-to-molecule propagation results in a continuous train of disturbances called a compression-rarefaction wave. If the frequency of motion is above 20,000 cycles per second (cps) the waves are referred to as ultrasonic compressional waves. A small group of these waves, which occur together and are not preceded or followed by other waves, is called a wave train or simply a pulse. A pulse may have one of several different forms depending upon the individual wave amplitude, and the way the waves build up and decay. The most used modes of vibration are longitudinal, shear, surface, and plate waves.

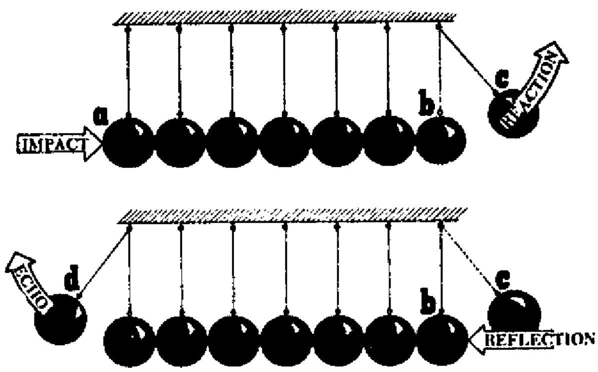


FIGURE 12. Mechanical analogy of wave propagation.

LONGITUDINAL WAVES:

The wave is said to be longitudinal (compressional) when the movement of the particles are parallel to the direction of the wave motion (see Fig. 13).

The longitudinal mode of wave transmission is probably the most widely used in ultrasonic testing and is also the easiest to see with respect to the method of propagation. This wave is easily generated and detected, and it has a high velocity of travel in most media. In most common materials, this type of wave has a short wave length in comparison with the cross sectional area of the transducer (probe). Because of this, the wave energy may be focused into a sharp beam with only a slight divergence. The main use of longitudinal waves is for the detection and location of defects that present a reasonably large frontal area to the surface from which the test is being made.

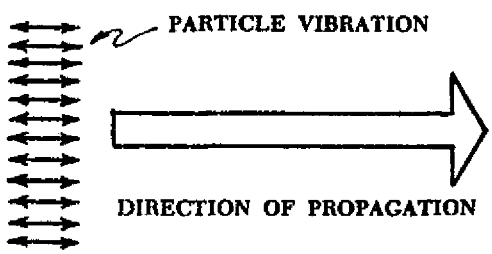


FIGURE 18. Longitudinal waves.

SHEAR WAVES:

The wave is said to be shear (transverse) when the movement of the particles are perpendicular to the direction of the wave motion (see Fig. 14). These waves have a lower velocity than do longitudinal waves (in steel and other metals, about half). Because of their slower speed, shear waves have shorter wave lengths than those of longitudinal waves of the same frequency. This shorter wave length makes shear waves more sensitive to small inclusions, and consequently they are more easily scattered within the specimen.

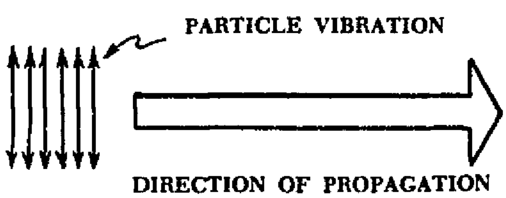


FIGURE 14. Shear waves.

The principle advantage of these waves is found in applications that require an ultrasonic beam to be transmitted into the test object at a small angle to the surface. (see Fig. 15).

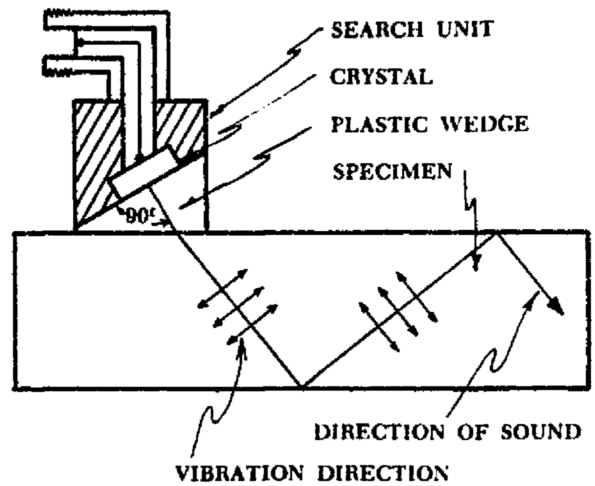


FIGURE 15. Transmitting a wave at a small angle.

SURFACE (RAYLEIGH) WAVES:

The principle of surface wave propagation was first described mathematically by Lord Rayleigh about 1875. Surface waves travel with little attenuation in the direction of propagation, but their energy decreases rapidly as the wave penetrates below the surface. Roughly, these waves may be likened to water waves traveling over a small body of water since they travel over the surface of a part penetrating only to a depth of about one wave length. The particle displacement of the wave motion follows an elliptical orbit consisting of both the longitudinal and shear wave motion (see Fig. 16).

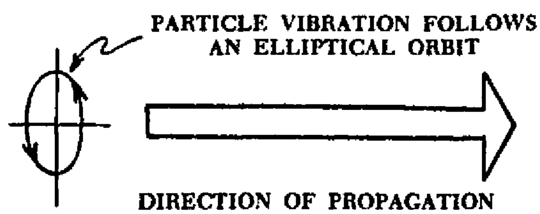


FIGURE 16. Surface waves.

Velocity of surface waves depends upon the material itself and is about nine-tenths of the shear-wave velocity. Surface waves are likely to be affected, in their propagation, by variations in hardness, plated coatings, shot peening, or surface cracks, and are easily dampened by dirt or grease on the surface of the specimen. Surface waves can often be produced as an unwanted effect, especially when the contact surface is rough.

The waves are not limited to flat surfaces. They will travel around curves and surface contours. Sharp corners, such as the boundaries of plates or flaws, will reflect these waves. In fact, it is this characteristic of traveling around contours which makes surface waves so useful in surface flaw detection (see Fig. 17).

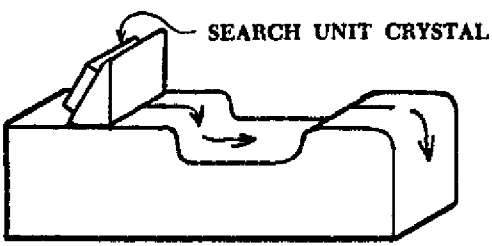


FIGURE 17. Surface-wave technique.

PLATE (LAMB) WAVES:

When ultrasonic vibrations are introduced into relatively thin sheet, the energy propagates in the form of plate waves. These waves are often referred to as lamb waves, which is considered incorrect, since, strictly speaking, lamb waves never occur in practice.

Unlike the longitudinal, shear, and surface modes, the plate-wave velocity is dependent both on frequency and plate thickness. A complex particle motion exists somewhat like the elliptical orbits described for surface waves. Theoretically, an infinite number of wave modes are possible. Greatly simplified, they can be divided into two basic types: The symmetrical type are known as dilational waves and the asymmetrical type as bending waves.

The asymmetrical mode can be described by relating their action to moving a rug by abruptly shaking one edge of it so that the motion ripples throughout its length.

The symmetrical mode can be demonstrated by abruptly and sharply pulsing one edge of, for example, a thin sheet of metal; the resulting wave travels down the sheet by successive thickenings and thinnings of the sheet itself. Examples of these two modes are illustrated in Fig. 18.

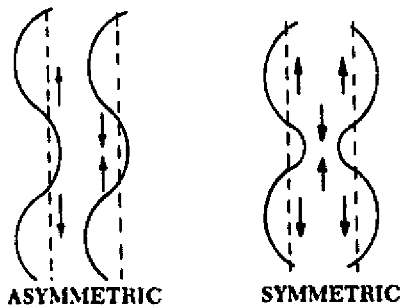


FIGURE 18. Plate waves.

Plate waves are excellent for detecting nonbonded areas in laminated structures such as sandwich panels or fuel elements. By sending plate waves along the outer surface, any areas of the top sheet that are not securely bonded in place can be made to vibrate in one of these modes. By sensing such local areas of vibration, lack of proper bonding can be detected. Plate waves can also be used to find radial cracks in tubing that extends as little as 1 mil beneath the surface, and to a much greater sensitivity than with shear waves.

ULTRASONIC VIBRATIONS

All mechanical testing methods involve much phenomena described by the fundamental laws of mechanics and acoustics. The various methods differ primarily in the frequency and magnitude of the stresses developed in the test material. Ultrasonics employ low-amplitude stresses which do not permanently affect a specimen because of the short wave lengths and relatively low energy of the ultrasonic vibrations which are transmitted through the material. On the other hand, destructive mechanical tests, such as static physical tests and forced vibration fatigue testing involves high-amplitude stresses. These high-amplitude stresses may cause heating, nonlinear effects, permanent deformation, and eventual rupture of the specimen.

Sound waves beyond the hearing range of the human ear are referred to as ultrasonic vibrations. The term embraces all vibrational waves of a frequency greater than approximately 20,000 cps. Ultrasonic vibrations of the lower frequencies act in essentially the same manner as do audible waves. Most commercial ultrasonic testing is done at frequencies from 200 kc. to 25 mc.; however, application exists for frequencies as low as 25 kc. per second and as high as 200 mc. per second.

In practical testing, selection of frequency depends on sensitivity desired and sound penetration required; high frequency for sensitivity and low frequency for penetration. In general, sound waves of all frequencies will penetrate fine-grain material. However, as the grain structure becomes more coarse, interference in the form of scattering may be expected when using higher frequencies (shorter wave lengths) and greater depth of penetration will be obtained by going to lower frequencies (longer wave lengths). The resonant frequency of a crystal is determined primarily by its thickness, the higher the frequency the thinner the crystal. For this reason crystals with frequencies above 10 mc. are generally considered too fragile for contact testing. All testing frequencies, however, can be used in immersion testing.

Ultrasonic vibrations have several important characteristics:

1. They travel relatively long distances in solid materials.
2. They travel in well-defined sound beams.
3. The velocity of a specific vibrational wave made is constant through a given homogenous material.
4. Most of the energy contained in one vibrational wave train is dissipated before the succeeding pulse is introduced to avoid confusing indications.
5. Vibrational waves will be reflected at boundaries of different elastic and physical properties.
6. Vibrational waves may change their mode of vibration when passing between materials having different elastic and physical properties or when reflected from boundaries at certain angles.

REFLECTION OF ULTRASONIC WAVES:

Reflection of the ultrasonic vibrations will occur at the boundary between two different materials if a mismatch of acoustic impedance is encountered. The ultrasonic beam will be reflected at the interface exactly like light waves. For instance, the silvered back of a mirror has a high-impedance mismatch to air, and light reflects from it at a very high efficiency. A plain piece of polished crystal glass has a very low impedance mismatch with air, and—consequently—reflects very little.

When ultrasonic energy impinges upon the interface between two different mediums, part will be reflected, and the rest will be allowed to pass into the second medium, depending upon the impedance ratio between the two materials. Also, the path traveled by the vibrations and whether they return to their source depends upon the angles at which the beam impinges upon the reflecting surfaces, as well as the number and location of these surfaces (see Fig. 19).

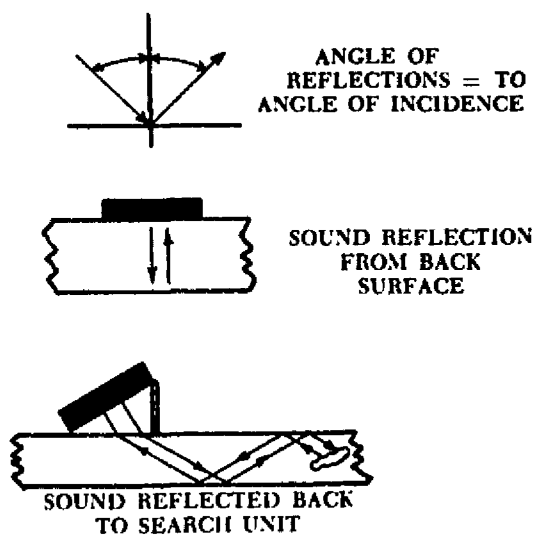


FIGURE 19. Reflection of ultrasound.

REFRACTION AND MODE CONVERSION OF ULTRASONIC WAVES:

Ultrasonic beams introduced at an angle into a specimen are refracted in accordance with Snell's law. More simply stated this means the velocities in the wedge material and the metal are different, therefore, the longitudinal vibrations will be refracted when passing into the metal (see Fig. 20). At certain angles, conversion to other modes of vibration, such as shear (see Fig. 21) and surface waves (see Fig. 22) occurs. The following formula may be used to calculate the wedge angle required to produce the desired inspection angle and mode for material using plastic, water, oil, or other wedge materials:

$$\frac{\text{Sin } \alpha}{\text{Sin } \beta} = \frac{c_1}{c_2}$$

Where: α = angle normal of the beam in the wedge

β = angle of refracted beam in specimen

c_1 = velocity of incident vibrations in the wedge (usually the longitudinal velocity)

c_2 = velocity of vibration in the material under inspection for the desired wave mode.

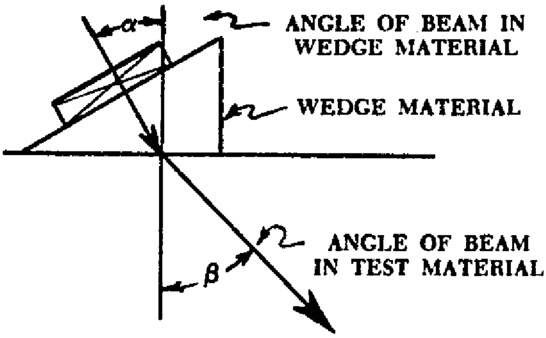


FIGURE 20. Refraction of the ultrasonic beam.

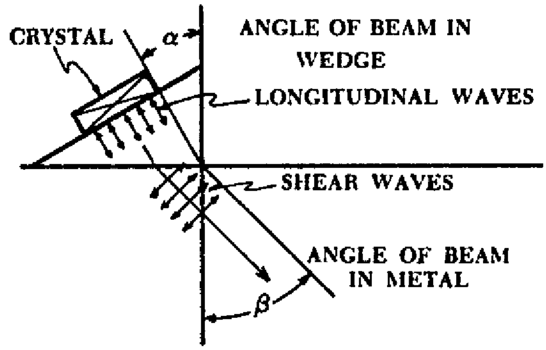


FIGURE 21. Generating shear waves.

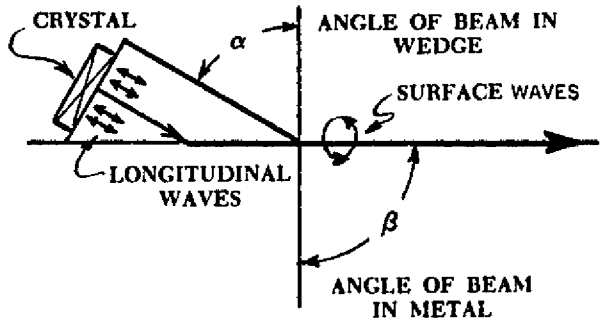


FIGURE 22. Generating surface waves.

BEAM DIVERGENCE:

Beam divergence varies with frequency and crystal diameter. The higher frequencies give more directivity to the sound beam. Also a large diameter crystal is more directive than one of a smaller diameter when operated at the same frequency (see Fig. 23).

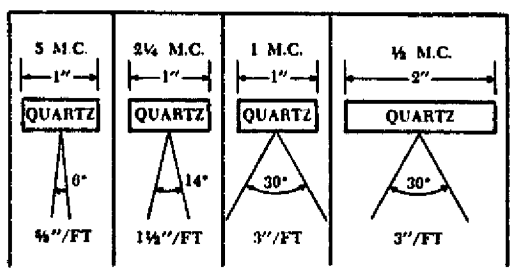


FIGURE 23(a). Beam divergence of sound waves in steel.

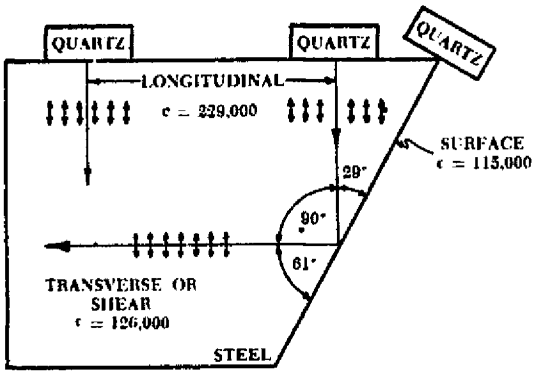
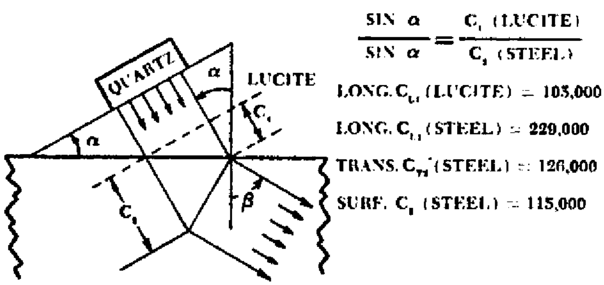


FIGURE 28(b). Diagram of longitudinal sound striking a surface at an angle.



α WEDGE ANGLES	β STEEL ANGLES	DOMINANT MODE OF VIBRATION
0 — 15	0 — 35°	LONGITUDINAL
27 — 55°	35° — 80°	TRANSVERSE
55 — UP	90°	SURFACE

FIGURE 28(c). Sketch showing why refraction must occur when velocities change.

FRESNEL OR NEAR-FIELD EFFECT:

The distribution of the ultrasonic energy in a beam can best be described by an analogical approach. Assume the transducer is not a single element but consists of thousands of tiny independent transducers and when excited, each sends out its own wave front. A scalloped wave front comprising the many overlapping waves of each radiating point would result. In the process of all of these individual waves overlapping and growing larger in diameter as they move away from their source, there will be areas where two or more will meet moving in the same direction at the same speed, or "in phase", and the energies of both will unite, creating a stronger area, while some will meet out of phase and cancel one another, creating areas of minimum energy.

As we move further from the transducer, the maximum energy areas converge toward the center, and the effect at this distance is of a single wave front. If a small signal were to be returned to the transducer before these many wave fronts had converged to a central point, it would most likely be lost or severely distorted by the comparatively large disturbance in this area. For this reason, and others, flaw detectors are said to be blind near the surface. How far this effect extends is a function of velocity, frequency, and transducer diameter.

MATHEMATICAL ANALYSIS OF THE ULTRASONIC TRANSMITTER BEAM PROFILE

Since the emission of ultrasonic waves by the transmitter takes place in a divergent beam with a beam angle y determined by the diameter D of the oscillator and the wavelength employed, according to the relationship:

$$\text{Sin } y = \frac{1.08}{D} = \frac{c}{fD}$$

Where: c = acoustic velocity

f = sound frequency (reduction of the amplitude to 10%)

D = diameter of the transducer.

But this only applies beyond a certain distance N_0. from the ultrasonic transducer. The region governed by N_0. is therefore known as the near field of the ultrasonic transducer, in contrast to the adjoining far field (see Fig. 24).

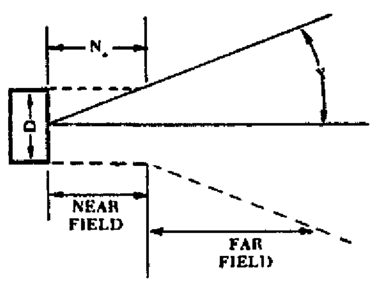


FIGURE 24. Sketch of the near and far fields of an ultrasonic transmitter.

In the far field the height of the echo produced by a very small flaw is, to a first approximation proportional to $1/\tau^2$*, whereas in the near field it varies appreciably owing to interference. For the length N_o of the near field the following equation applies:

$$N_o = 0.25 \frac{D^2}{\lambda} = 0.25 \frac{D^2 f}{c}$$

Where: λ = wavelength

D = diameter of the ultrasonic oscillator

c = acoustic velocity

f = frequency of the sound.

*τ = Pulse width in microseconds.

The difference between the near and far fields is important in practice since visual and automatic interpretation of flaw size requires recognition of the continuous change in echo signal from a given flaw as a function of its distance from the testing surface. This change is nonlinear and usually bidirectional, i.e., the response increases for a short distance (near-field zone), reaches a peak (near-field limit) and then continues to decrease throughout the remainder of the test piece (far-field zone) (see Fig. 25).

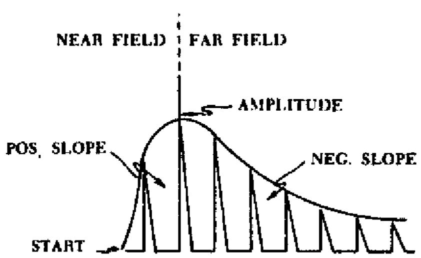


FIGURE 25. Signal response of the echo signal.

Ultrasonic testing equipment provides for the correction of signal response in both zones by controlling the relationship between gain and depth in a selected depth range by a sensitivity time control or swept gain control to compensate for the natural decrease in echo height due to attenuation or divergence of the beam.

To give essentially a flat response regardless of defect distance from the entrant surface, Sperry utilizes a Distance Amplitude Correction (DAC) unit. Use of the DAC component is facilitated by the simultaneous display of both video signals and DAC curve. The set-up consists of adjusting the displayed curve to a known or experimental distance amplitude characteristic. This may be plotted directly on the cathode-ray tube (CRT) screen or applied as a transparent overlay.

ULTRASONIC SYSTEMS

There are two basic ultrasonic systems; pulsed and resonance.

PULSED:

The pulsed system may be either echo or through transmission. The echo is the most versatile of the two pulse systems.

ECHO:

Flaws are detected by measuring the amplitude of signals reflected and the time required for these signals to travel between specific surfaces and the discontinuity (see Fig. 26).

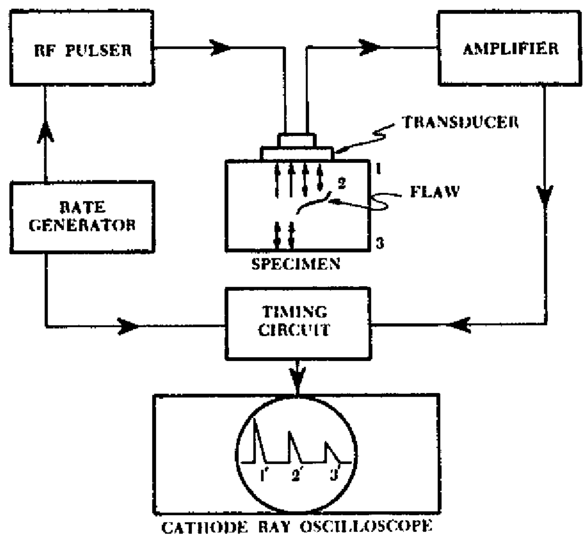


FIGURE 26. Block diagram of basic pulse-echo system.

The time base, which is triggered simultaneously with each transmission pulse, causes a spot to sweep across the screen of the CRT. The spot sweeps from left to right across the face of the scope 50 to 5,000 times per second, or higher if required for high-speed automated scanning. Due to the speed of the cycle of transmitting and receiving, the picture on the oscilloscope appears to be stationary.

A few microseconds after the sweep is initiated, the rate generator electrically excites the pulser and the pulser in turn emits an electrical pulse. The transducer converts this pulse into a short train of ultrasonic sound waves. If the interfaces of the transducer and the specimen are properly orientated, the ultrasound will be reflected back to the transducer when it reaches the internal flaw and the opposite surface of the specimen. The time interval between the transmission of the initial impulse and the reception of the signals from within the specimen is measured by the timing circuits. The reflected pulse that is received by the transducer is amplified, then transmitted to the oscilloscope where the pulse received from the flaw is displayed on the CRT screen in the same relationship to the front and back pulse as the flaw is in relation to the front and back surface of the specimen (see Fig. 27).

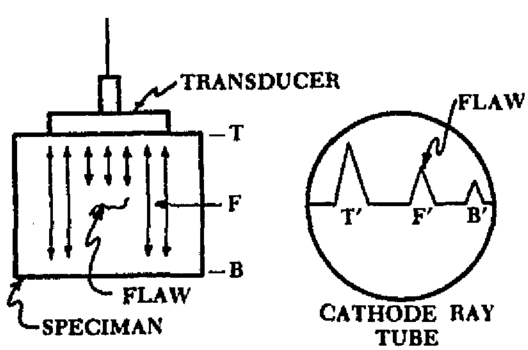


FIGURE 27. Oscilloscope display in relationship to flaw location.

Figure 28 illustrates an ultrasonic thickness indicator that is basically a pulse-echo instrument. In operation, a pulser excites the transducer and logic circuitry. The transducer sends out an ultrasonic wave and transforms reflected acoustical energy which it receives back into electrical signals. The logic circuitry then selects certain of these electrical signals to operate a gate. The gate period is a function of the material thickness. A precision oscillator, selected to match the acoustical properties of the specimen material, passes a number of cycles through the gate while it is open. A counter records these cycles and indicates directly the thickness of the material in inches. The technique is refined by specialized logic to ensure that spurious pulses cannot cloud the measurement.

Control functions have been cut to a minimum and an illuminated "Nixie" readout provided.

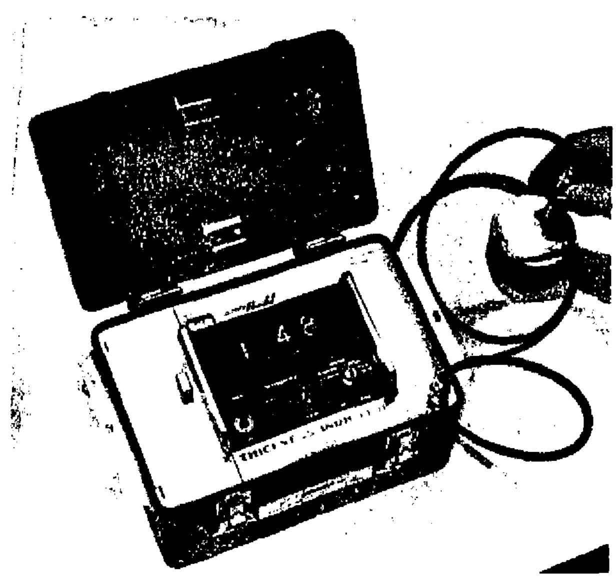


FIGURE 28. Digital thickness indicator.

THROUGH TRANSMISSION:

This system uses only amplitude information and operates on the principle that certain specific changes in the sample will produce significant changes in the intensity of an ultrasonic beam passing through it. This system requires two transducers placed on opposite sides of the specimen (see Fig. 29). One transducer transmits the wave through the piece and the other picks up the signal. If there is a defect in the path of the wave, the received indication is reduced in size to the degree that the signal is blocked. This system is seldom used for weld testing, it is used extensively for bond testing of bimetals and clad materials where the area of a laminar-type defect is of interest, and its probable depth is either known or of no importance.

This system is also useful in testing for metallurgical changes due to heat, pressure stress, and fatigue. For these purposes, a frequency of 10 mc. or higher is selected. Grain boundary at these frequencies becomes a definite factor in the transmission of energy. Any change in the lattice structure or slip planes is readily discernable as a change from a normal condition of energy transfer.

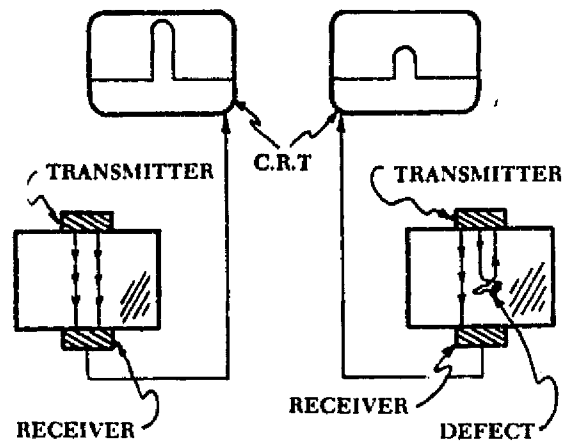


FIGURE 29. Through-transmission technique.

RESONANCE:

This system differs from the pulse method in that the frequency of transmission is, or can be, continuously varied. The resonance method is principally used for thickness measurements when the two sides of the material under test are smooth and parallel. The point at which the frequency matches the resonance point of the material under test is the thickness determining factor. It is necessary that the frequency of the ultrasonic waves, corresponding to a particular dial setting, should be accurately known. Checks should be made with standard test blocks to guard against possible drift of frequency. If the frequency of an ultrasonic wave is such that its wave length is just twice the thickness of a specimen, then the reflected wave will arrive back at the transducer in the same phase as the original transmission so that strengthening of the signal, or a resonance, will occur. If the frequency is increased so that three times the wave length equals four times the thickness, then the reflected signal will return completely out of phase with the transmitted signal and cancellation will occur. Further increase of the frequency, so that the wave length is equal to the thickness again, gives a reflected signal in phase with the transmitted signal and resonance occurs once more. By starting at the fundamental frequency, where the wave length equals twice the thickness, and gradually increasing the frequency, the successive cancellations and resonances can be noted and the readings used to check the original, or fundamental, frequency reading (see Fig. 30).

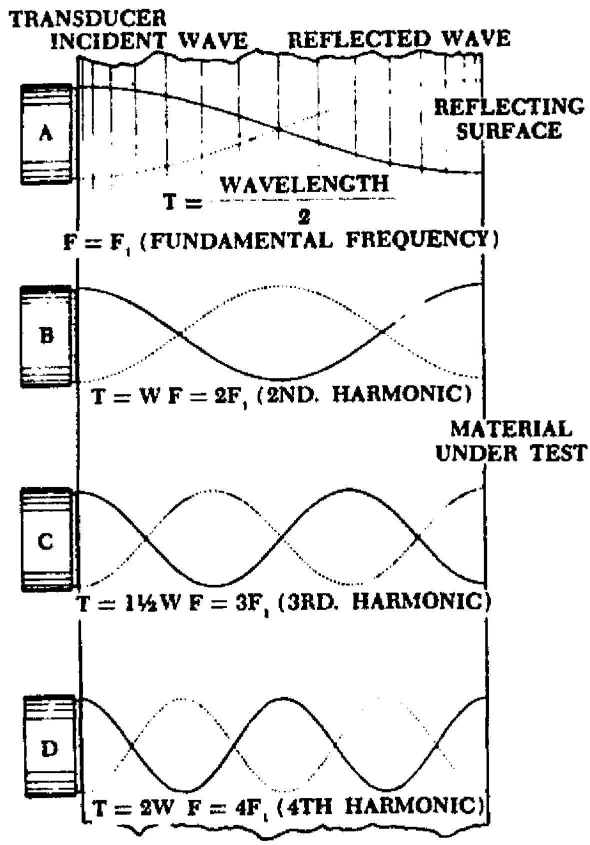


FIGURE 30. Conditions of ultrasonic resonance in metal plate.

In some instruments, the oscillator circuit contains a motor-driven capacitor which changes the frequency of the oscillator (see Fig. 31). In other instruments, the frequency is changed by electronic means.

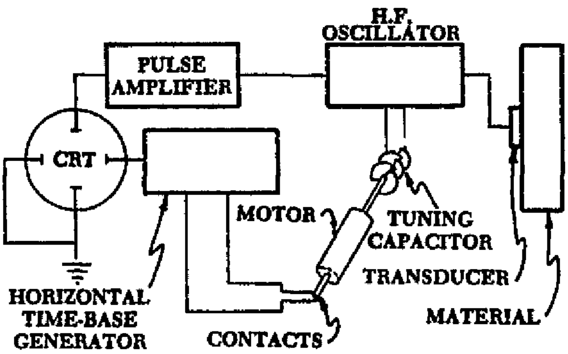


FIGURE 31. Block diagram of resonance thickness measuring system.

The change in frequency is synchronized with the horizontal sweep of a CRT. The horizontal axis thus represents a frequency range. If the frequency range contains resonances, the circuitry is arranged to present these vertically. Calibrated transparent scales are then placed in front of the tube and the thickness can be read directly. The instruments normally operate between 0.25 mc. and 10 mc. in four or five bands.

The resonant thickness instrument can be used to test the thickness of such metals as steel, cast iron, brass, nickel, copper, silver, lead, aluminum, and magnesium. In addition, areas of corrosion or wear on tanks, pipes, ships' hulls, airplane wing skins, and other structures or products can be located and evaluated.

Direct-reading, dial-operated units are available that measure thickness between .025″ and 3.00″ with an accuracy of better than ±1% (see Fig. 32).

The wall-thickness meter utilizes a resonant circuit tuned to a train of multiple echoes. After tuning the meter, measurements of wall thickness between 4 and 60 mm. of steel can be read directly off the scale (accuracy is about 1% for thickness over 10 mm. provided the surface is good). For materials other than steel, the wall-thickness meter may be recalibrated or previously determined conversion factors (i.e., the ratio of the respective sound velocities) may be used.

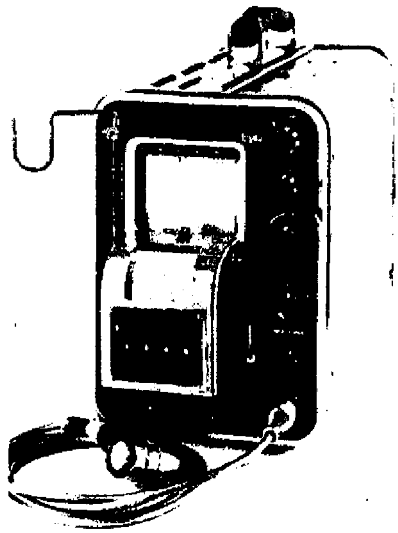


FIGURE 32. Wall-thickness meter attached to the front of ultrasonic flaw detector.

PRESENTATION

There are several methods of observing and recording ultrasonic response patterns such as a CRT; indicating lights, alarm devices (bells, buzzers, etc.); paint-spray markers, strip-chart and facsimile recorders, photographic representations (see Figs. 33, 34, and 35) go/no-go monitors, and others.

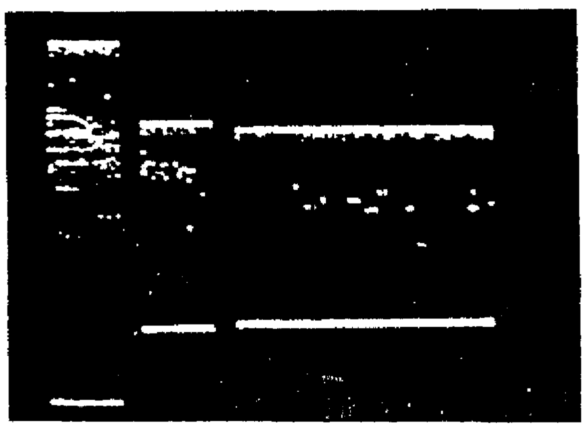


FIGURE 33. Longitudinal view of a cross-sectional record of a forging ("B" scan).

These various methods may be used in combinations to suit a particular need.

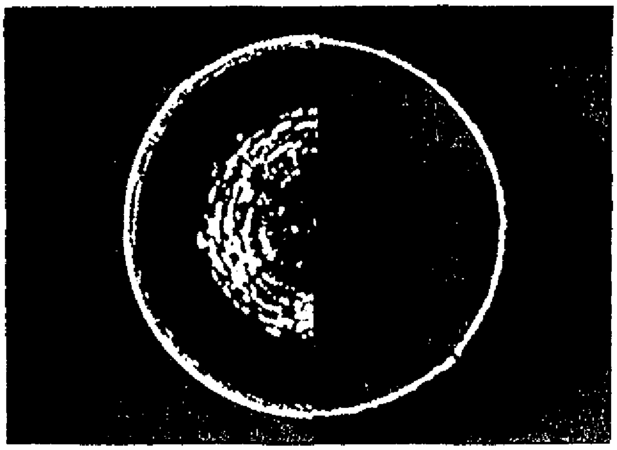


FIGURE 34. Radial view of a cross-sectional record of a forging ("B" scan).

FIGURE 35. Cross-section recorder with special camera ("B" scan).

The cross-section recorder gives a photographic representation of the condition of a forging along the entire length of the specimen or in any selected radial plane. The Ultrasonic Flaw Detector is used in conjunction with the monitor and a Polaroid Camera. The camera provides the finished record 10 seconds after exposure. When recording a longitudinal cross-section, the probe is moved along a line on the outside of the specimen in preselected steps. At each point a contact is actuated, with the result that the dotted trace on the recorder screen shifts gradually from one side of the screen to the other. For radial cross-sections, pressing the button causes the fluorescent tube with its dotted trace to rotate about its axis by a small angle. The cross-sectional record thus yields a chart showing the distribution of flaws across the section of the specimen.

CATHODE-RAY TUBE OR (CRT):

Size:

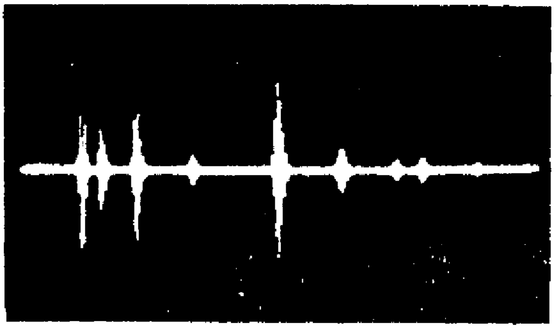
The screen sizes vary from 3″ to 12″, however, there is usually no need for providing a signal larger than that which can be presented by a 5″ tube. The large screens do not provide any more picture information. Usually a small tube will have better contrast and definition. The primary purpose in using a large screen is in automated systems where the scanning transducer must be positioned some distance from the viewing screen of the test instrument.

Signal Trace:

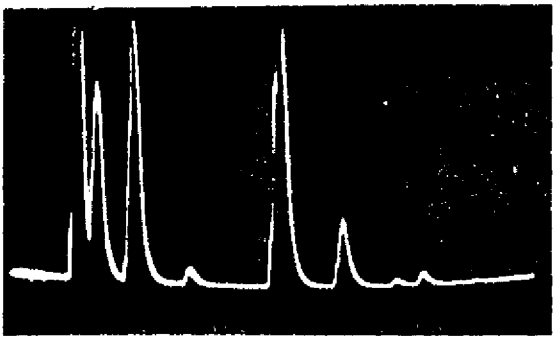
Figure 36 shows the two most common trace presentations. The Radio-Frequency (RF) presentation exhibits signals both above and below the sweep line. This type of presentation provides maximum resolution for locating defects close to the surface or for separating signals following closely upon one another. The video trace presentation is a cleaner and less cluttered signal than the RF presentation, however, it provides for less signal resolution because of its broader pulse characteristics. The video presentation is, in fact, an RF presentation with the bottom half electronically clipped off and only the outline of the original pulses, added on to the top half, is shown. Therefore, larger signals are indicated, but flaw definition is more limited. Of the two traces, the video is most commonly used because it is easier to read.

Range Markers:

To provide a means of measuring the depth of a flaw indication, square waves are electronically superimposed on, or beneath, the regular sweep line of the test presentation. The lengths of these waves can be adjusted to represent inches or feet of the material being tested. Figure 37 shows three of the most commonly used types of wave markers.



RF



VIDEO

FIGURE 36. Radio-frequency trace and video trace.

The square-wave markers shown at the top are easy to distinguish from the spike-like echo signals. They generally provide the most precise means of measuring flaw depth. The pyramidal markers (center) are especially useful in an angle-beam test where the sonic energy is sent into a piece at an angle and bounces back and forth between the walls as it travels on through the part under test. These markers simulate the actual path of the search beam passing through the piece, making it easier to determine the flaw depth with respect to the top and bottom surfaces of the specimen. The bottom marker illustrated differs from the other two types in that it does not have equal positive and negative values. These markers are a compressed negative wave and deflect in the opposite direction to the echo signals.

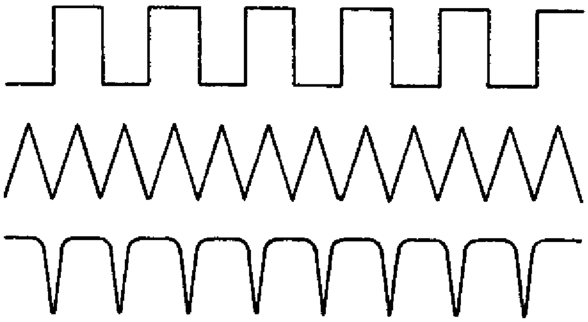


FIGURE 37. Types of marker systems.

SCAN PRESENTATIONS:

The ultrasonic echoes are electronically translated into visual presentations on the CRT. There are three different presentations available; the A-scan; B-scan; and C-scan:

A-scan—

In the A-scan presentation, the horizontal base line on the screen indicates elapsed time (from left to right) and represents the depth of the test specimen. The vertical deflection shows response amplitude. The signal amplitude represents the intensities of transmitted or reflected beams. This may be related to flaw size, sample attenuation, or other factors (see Fig. 38).

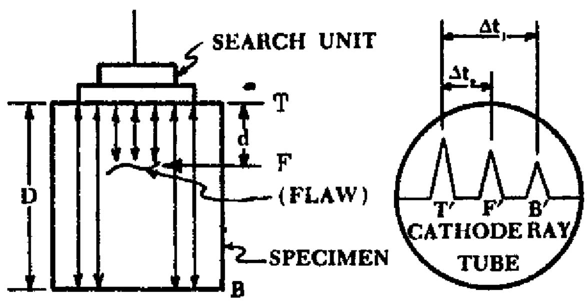


FIGURE 38. A-scan presentation.

$T^1F^1B^1$ are reflections from boundaries T, B, and F. If D is the measured thickness of the specimen, and d the depth of the flaw, then d is determined by

$$d = D\left(\frac{\Delta t_2}{\Delta t_1}\right)$$

B-scan—

The B-scan takes the same signals received by the A-scan and presents them in a different pattern. The location and depth of the flaw can be determined as in the A-scan, but, in the case of small defects, only a rough estimation of the flaw size can be obtained (see Fig. 39). The B-scan presentation was used mostly in the testing of plate stock for laminations, and is seldom used today.

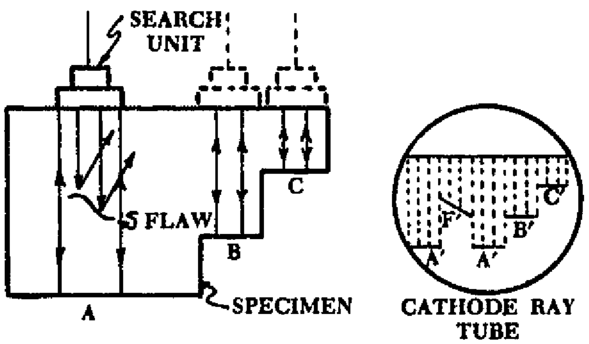


FIGURE 39. B-scan presentation.

C-scan—

The C-scan presentation is a plan view of the part under test; a flaw is indicated in a manner similar to that given when an X-ray is taken of a part. The electron beam follows the movement of the probe and traces a true-to-scale reproduction on the CRT. However, accurate flaw depth cannot be determined from the C-scan presentation (see Fig. 40).

Since the C-scan presentation is a true-to-scale reproduction of the flaw, the CRT is used only for calibration, tuning, and visual monitoring the test. The use of facsimile-type paper recorders are currently supplementing the CRT.

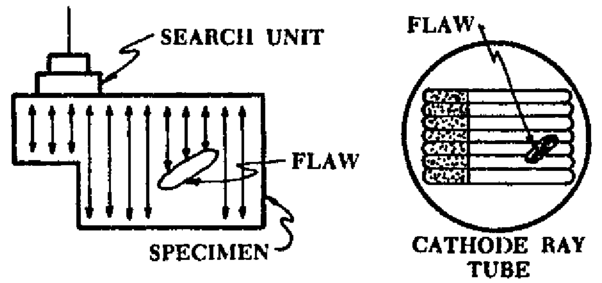


FIGURE 40. C-scan presentation.

The recorders provide excellent resolution, a permanent record, and are available with paper widths up 36″ by several hundred feet in length. By varying intensities, ranging from black to light grey, the depth of a defect can be approximated on the facsimile recorder.

INDICATIONS:

It is impossible to illustrate in this manual every possible variation of displays presented by the CRT. Fortunately the great majority of patterns will fall into one or another of ten basic types which are illustrated and explained in the following paragraphs. The operator will quickly learn to classify a type of presentation, even though the details are not identical to the prototype illustrations presented. Before the ultrasonic system can give results, as outlined in the following figures, it must, of course, have been properly set up and adjusted, using standard reference blocks (see Figs. 41 through 50).

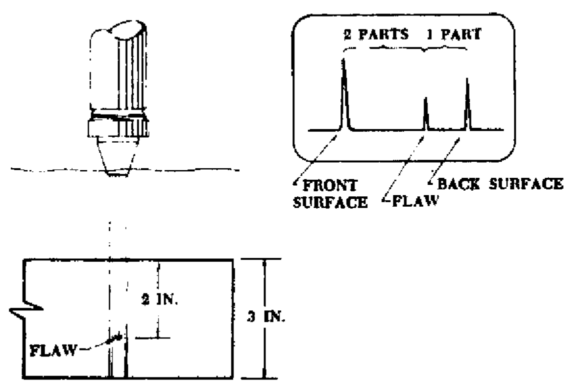


FIGURE 41. Immersion crystal focused on test block and indications to be expected.

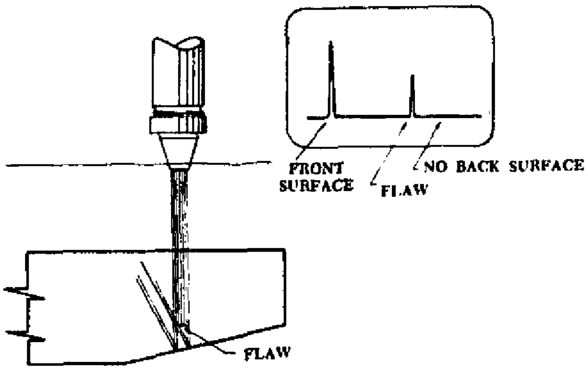


FIGURE 42. Immersion crystal focused on block with defect and non-parallel surface.

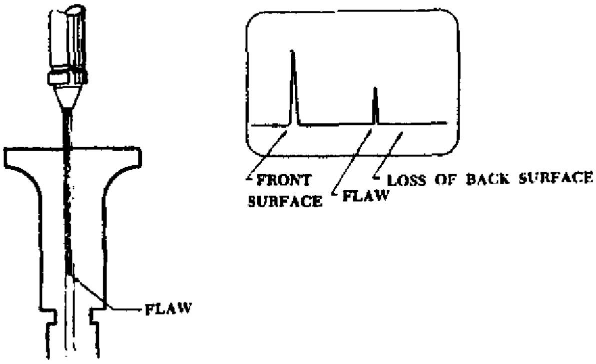


FIGURE 43. Immersion crystal focused on shaft too long for back reflection to return.

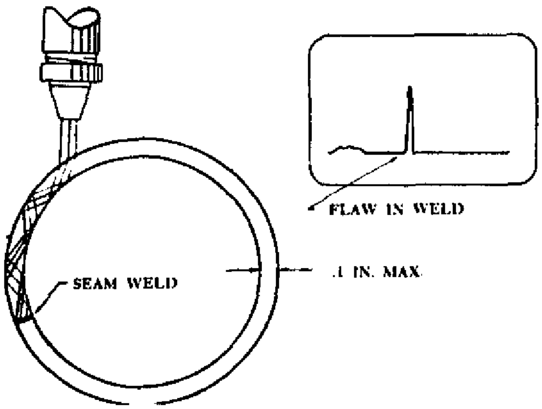


FIGURE 44. Angle beam penetrating a weld bead.

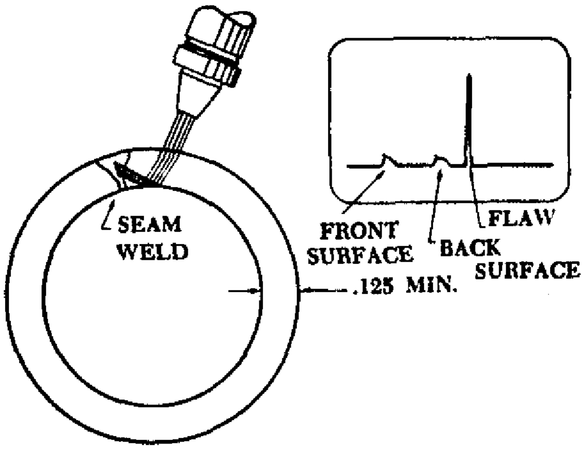


FIGURE 45. Angle beam penetrating a weld bead.

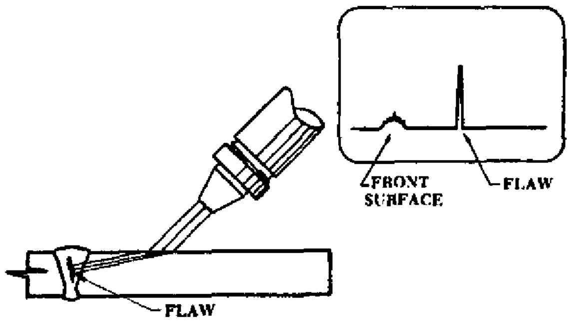


FIGURE 46. Angle beam penetrating a flat plate.

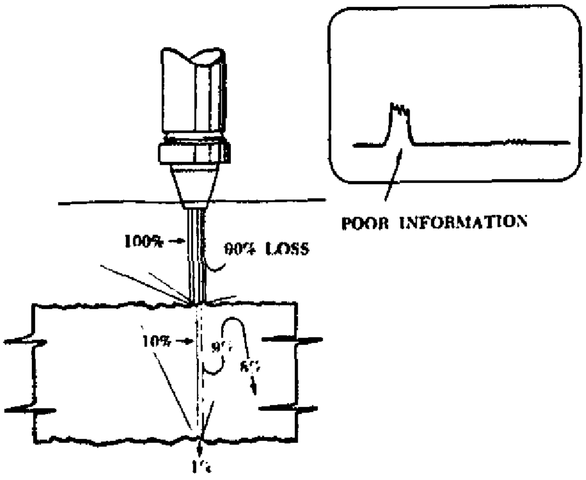


FIGURE 47. Results of rough front and back surfaces.

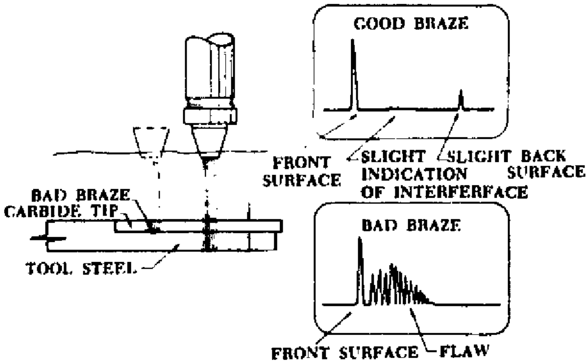


FIGURE 48. Evaluating braze of carbide tip to steel.

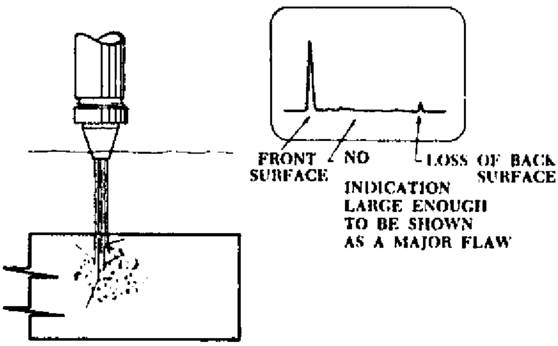


FIGURE 49. Indication received from porous material.

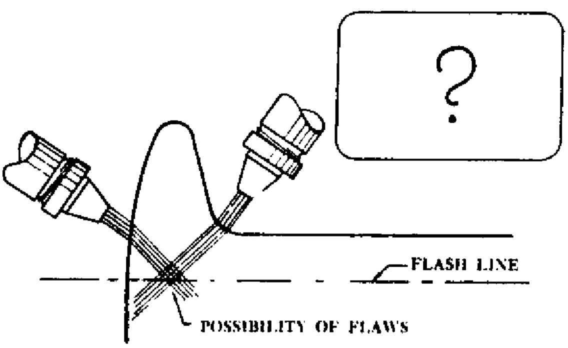


FIGURE 50. Irregular part.

Figure 41 represents a smooth-surfaced rectangular or round block with parallel surfaces placed directly under the search tube and at right angles to it. In such a case, clear pips representing the front and back surfaces of the material will be seen, and any flaw pips which are present will appear between these two.

The echo from the front surface of the metal returns first and is located at the left-hand side of the screen. The echo from the back surface of the sample arrives last and so is located at the extreme right of the screen. A pip which is located two-thirds of the distance from the front echo to the back echo indicates a flaw which is two-thirds of the thickness of the sample below its upper surface. For instance, if the sample is 3″ thick, and the pip appears on the right-hand side of the screen at two-thirds of the distance between the pips, measured from left to right, then the flaw is located 2″ below the surface. If the flaw is sufficiently large, all of the remaining sound may be reflected from it. In this case, the back echo will disappear, and the flaw will cast an ultrasonic shadow on the back surface.

Figure 42 illustrates a situation in which the back surface of the sample to be tested is not parallel to the front surface. Under these circumstances, when the sound waves reach the back surface they will be reflected at an angle in the same manner as a beam of light would be reflected, and so they will not return to the crystal. This means, of course, that the pattern on the screen will not have a right-hand pip, which represents an echo from the back surface. If a second pip does appear, it probably represents a flaw. If any question exists as to whether this second pip is a flaw or an echo from the back surface, a distance measurement will indicate which it is. Any flaws will, of course, appear on the screen at a distance less than the actual thickness of the material being tested.

Figure 43 indicates a situation where the depth of the metal through which the sound waves have to pass is so great and the nature of the metal is such that all of the sound waves are absorbed so that the echo, if any, from the back surface of the material is unable to get through. Again, of course, any pip to the right of the one representing the front surface will represent a flaw. In such a case, a distance measurement will clearly indicate that the flaw is close to the front surface.

In Figure 44, the item being tested is a seam weld on a piece of thin-walled tubing. Behavior characteristics of ultrasound at an acute angle of approach are such that some of the sound waves will be reflected from the surface and be lost. The rest of the waves will become trapped in the circular path of the metal, and very little echo will be received from either the front surface or the back surface. Those waves which are proceeding through the wall of the tubing will strike any obstruction in the wall at approximately right angles, and will return an echo from such an obstruction. If the tube has been inspected prior to welding and found to be free of flaws, then any flaw which shows up after welding must be in the weld or the weld bead.

Figure 45 represents the inspection of a welded tube with a wall thickness in excess of 0.125″. Refraction conditions are such that pips may be obtained representing both the outer and inner surfaces of the tube together with pips from any flaws which may be in the tube. The differences between the results received in Figs. 44 and 45 situations are due to the beam angles.

Figure 46 represents the inspection of a weld in a heavy plate. The rough surface of the weld bead prevents a direct overhead inspection of the weld zone because the ultrasound beam cannot enter near the surface of the rough bead. Therefore, the transducer must be directed so the sound beam will be refracted to strike the flaw at right angles. The ultrasound, when it leaves the couplant and enters the metal, will refract in such a way that the beam will be bouncing between the surfaces of the material.

When an ultrasonic beam enters metal at some angle other than normal to the surface, the internal angle will change rapidly with small changes in the external angle. If the internal deviation angle exceeds approximately 15°, both shear and longitudinal waves will result. Above 33°, longitudinal waves will disappear. Shear waves will produce the same indications on the screen as longitudinal waves. To produce shear waves in steel, set the transducer to some angle above 33°.

In shear-wave inspection, a rather small and poorly defined echo is obtained from the front surface of the specimen. However, a strong echo will be returned from vertical fissures, or cracks, in the material being inspected. If the searching tube is moved horizontally without changing its angle, the flaw pip will move toward or away from the surface pip. This is because the acoustic path between the front surface and the flaw is made shorter or longer by the motion of the searching tube.

Figure 47 represents a situation in which the front surface of the metal is so rough that a complete scattering of the sound waves results. In such a situation, no appreciable penetration into the metal will occur and any echoes that ordinarily appear on the screen will also be dissipated by the roughness and will not be received. The only possible solution to such a problem is either to have the surface smoothed sufficiently to allow normal reflection and penetration, or to conduct the test through a smoother surface from another angle. It is also suggested that the lowest frequency possible be used.

Figure 48 represents a typical reading from two different materials that have been brazed or welded face-to-face. Where a good uniform bonding has been obtained, a clear reading will be received with normal front and back pips, and a series of very small ridges. These ridges represent the uneveness of the bonded surfaces. If, however, the bonding is faulty and a void exists between the two surfaces, the sound waves will be unable to penetrate the void, and the pip from the bottom plate will be lost entirely, and a series of pips like tall grass will appear after the front surface indication which represent reverberations of the sound waves within the top plate.

Figure 49 represents an inspection of relatively porous material. The front pip will be clear, but the back pip will be either very small or nonexistent because the ultrasonic waves have either been absorbed or dissipated by the porous nature of the material. The clear pip of the front surface will probably be followed by a long series of bumps, or very short "grass", which represents tiny echoes received from the porous structure itself and do not actually represent flaws. If a significant flaw is located within the material, it should create a pip of sufficient size to be recognized. Ultrasound will not, however, penetrate deeply into exceptionally porous material. As shown in Fig. 47, lower frequencies penetrate more readily than higher frequencies. As shown in Fig. 42, distance measuring will ascertain that pips are not actually an echo from the back surface.

It may be necessary to inspect a sample involving complex curved surfaces which do not fit any of the preceeding illustrations. In such cases, the sound should be directed to hit the flash-line zone or grain flow at right angles since flaws would be oriented along the flash line or the grain flow direction. As shown in Fig. 50, the probes are improperly positioned, therefore, any indications received would be erroneous.

RECORDERS

The recording of flaws may be either by deflection modulation or intensity modulation.

DEFECTION MODULATION, CONVENTIONAL PEN-CHART RECORDERS:

In the deflection modulation method of recording, a pen draws a continuous line on a chart (see Fig. 51). When a flaw is detected, the line is deflected from its true path in proportion to the flaw amplitude. Pen-deflection recorders may use more than one channel, for example:

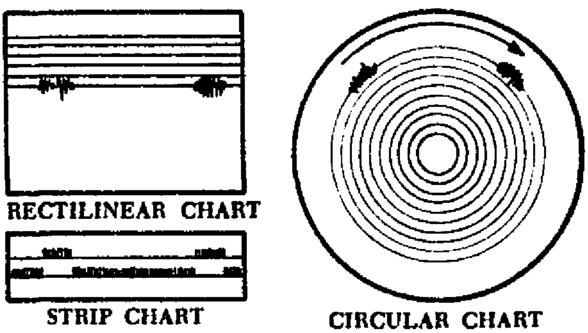


FIGURE 51. Various recording charts.

Channel 1—A-scan, flaw channel, recording of the echo amplitude.

Channel 2—A-scan, monitor channel, provides a constant check on actual testing sensitivity.

INTENSITY MODULATION, C-SCAN METHOD OF FACSIMILE RECORDING:

Figure 52 illustrates an Alden or ALFAX facsimile recorder in operation. This is an electrosensitive dry paper recorder. A helix wire on a drum rotates under a cross wire over which the paper rides, electrical sparks jump from the helix wire to the cross wire printing a plan view of the test piece on the electrosensitive dry paper. A true-to-scale reproduction of defects or a change in material density is indicated by various intensities ranging from black to light grey (see Fig. 53). When testing plate or other relatively flat specimens, the recorder prints a plan view of the test piece showing defect location and relative defect size. When testing material on a rotating mechanism, a true position along the X axis of defects detected is shown. When testing cylindrical components on a turntable, the true position along the Z axis of flaws detected is shown. When conducting a spiral scan of a disc which is mounted on the testing turntable, the recording chart is also mounted on a turntable that rotates in synchronism with the testing turntable.

ELECTRONIC GATING

One of the most important functions required in a high-speed ultrasonic testing system with automatic readout or control, is the selection and processing of only those signals from discontinuities which occur within particular zones or areas of the test piece. This is accomplished by establishing a specific controllable gated zone within the test piece (see Fig. 54). Signals above a pre-set amplitude occurring within the gate, can be monitored automatically and used to operate visual or aural alarms, sorting deflectors, or paint-spray markers.

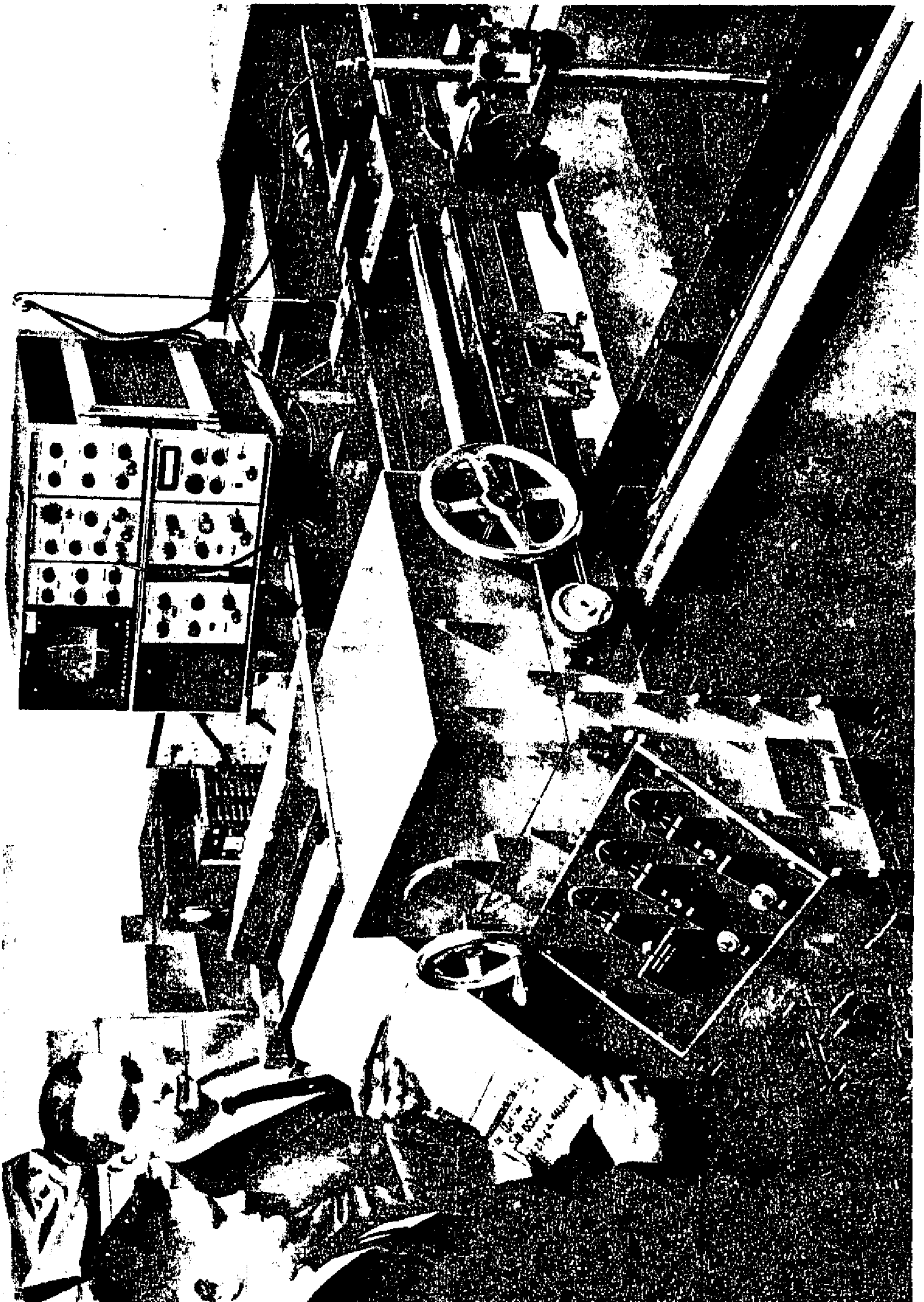


FIGURE 52. Facsimile recorder.

FIGURE 53. Ultrasonic recording of brazed honeycomb panel.

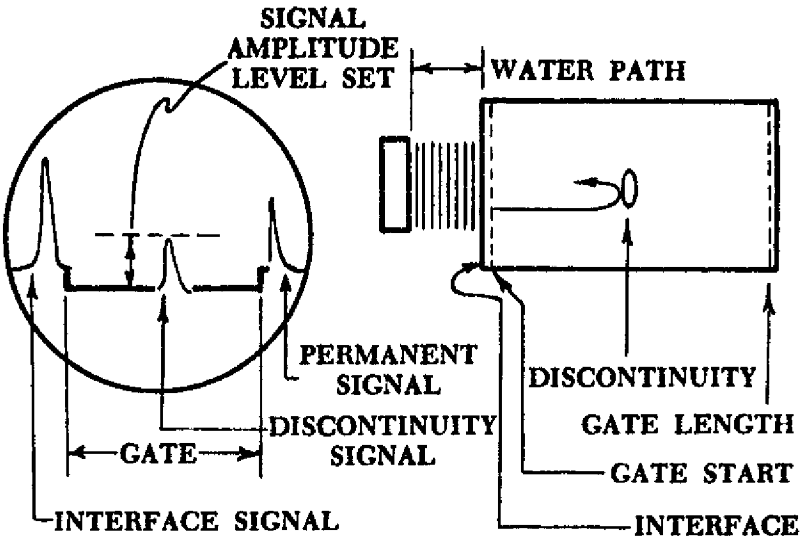


FIGURE 54. Controllable gated zone in test piece.

BASIC OPERATING PRINCIPLES OF GATES:

A gate is a device having several inputs and one output. Some of the inputs may be called signal inputs and others may be designated as control or selector inputs, although often the inputs are indistinguishable from one another.

There are two general classes of gates. The first, called the transmission or linear gate, is defined as one in which the output is approximately a replica of one of the inputs, but the output occurs only during times selected by the control inputs. Thus the gate transmits the signal from input to output in a linear manner during selected times.

The second class of gate, called the switching or logical gate, is defined as one in which the output is a pulse which may have no resemblance to any of the inputs, except that the pulse occurs during the interval selected by the control voltage.

The gate of Fig. 55 is suitable for a positive-going input signal. The gate signal (also called a control pulse, a selector pulse, or an enabling pulse) is a rectangular wave form which makes abrupt transitions between the negative levels $-E_1$ and $-E_2$. When the gate voltage is $-E_1$, the diode is heavily back-biased and there will be no response at the output to an input signal unless the peak amplitude of the input signal is larger than the magnitude of the back-biasing voltage. When the gate rises to its higher level $-E_2$, a time-coincident signal input pulse may be transmitted to the output.

In Fig. 56, $-E_2$ is assigned a value of minus 5 volts, and for a 10-volt input pulse, a 5-volt output pulse appears. The level $-E_2$ may be adjusted so that only that part of the signal desired appears at the output. When used in this manner, the circuit is referred to as a threshold gate.

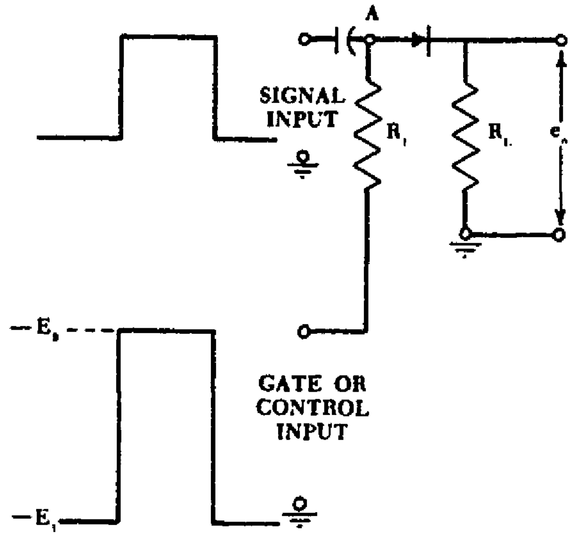


FIGURE 55. Threshold gate circuit diagram.

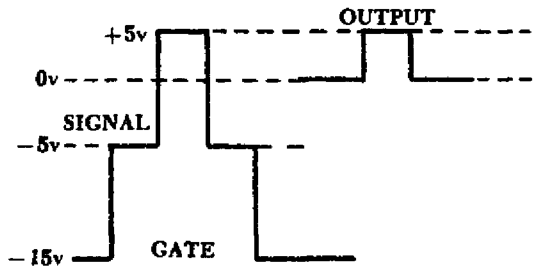


FIGURE 56. Threshold gate wave form.

DELAY LINE

By using a delay unit to increase resolution power, "close-to-surface" defects, such as those normally found in spot welds, may be investigated and evaluated.

The basic operation of a delay line depends on the fact that acoustic signals travel much slower than electrical signals. At the input end of the line, the electrical signal to be delayed is converted to an acoustic signal by a transducer.

The signal travels along the delay line as an acoustic wave, requiring a specific time to travel to the output end. At the output end, the signal is converted back to its electrical form by another transducer. Figure 57 illustrates one of a number of methods which may be used to delay or slow down the electrical signal by converting it to the slower traveling sound waves.

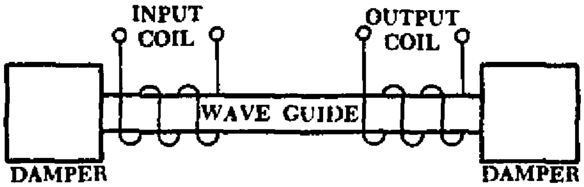


FIGURE 57. Ultrasonic delay line

The ultrasonic delay line shown employs an input and an output transducer coil with a magnetostrictive core which is attached to a sonic wave guide. At the input end, the flux changes in the coil caused by the electrical input signal set up mechanical stress (vibrations) in the core. These vibrations travel down the line to the output coil. Acoustic absorbers (dampers) are used at both ends of the line to prevent reflections along the wave guide, which would introduce a form of distortion. A given amount of delay can be accomplished by using different lengths of line.

COUPLANT

Ultrasound generated by the piezoelectric effect, for all practical purposes, will not propagate in air due to its high frequency and short wave length. The actual movement of a piezoelectric crystal vibration is in the micron range; it is often described as acceleration without motion. To transmit such a small amount of energy into a material, it is necessary to use a fluid couplant between the search unit face and the material surface. A film of oil, glycerine, or water is generally used (see Figs. 58 and 59). When water is used as the couplant, a wetting agent should be used to eliminate surface tension and facilitate "wetting" of the surface. When it is either impracticable or undesirable to use oil or water, a couplant paste is used.

A couplant is not required when ultrasonic waves are generated by means of the magnetostrictive effect in the test piece.

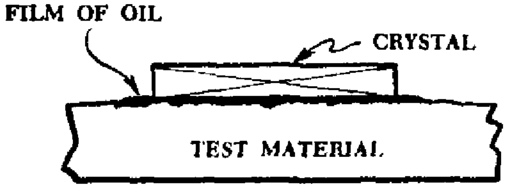


FIGURE 58. Couplant (contact testing).

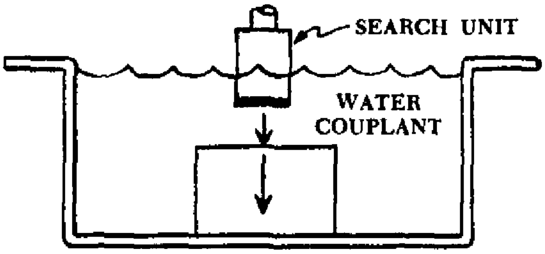


FIGURE 59. Couplant (immersion testing).

ULTRASONIC REFERENCE BLOCKS

Standard Reference Blocks are used to standardize the ultrasonic equipment, set the sensitivity, and evaluate the discontinuities in the material being inspected. These blocks provide the comparison for any combination of crystal size, frequency, or test instrument used to inspect materials. The evaluation of the discontinuities within the material is accomplished by comparing the ultrasonic response from the discontinuity with the known artificial defects (flat-bottomed holes or notches) in the Standard Reference Blocks. The test instrument should be adjusted to indicate the hole representing the smallest defect it is desired to pick up. This adjustment represents a lower standard of the instrument. *When making a test set-up, care should be taken to assure that the test block is of the same formulation alloy with similar surface conditions as the material under test.* This precaution is necessary to assure that distance calibration is correct. Some aluminum blocks are fabricated from ultrasonically selected 7075-T6 rolled bar and tested to the requirements of ASTM E 127-64. Alcoa type 1 blocks are used where good electrical contact is required. Alcoa type 2 blocks are anodized for resistance to corrosion resulting from immersion or environment. Some steel blocks are fabricated from type 4130N or 4340 alloy to the ASTM E 127–64 dimensions; however, steel blocks are not covered by the ASTM specification. If any adjustments are made on the apparatus, or if the probes are changed during the test, the probe and apparatus should be checked again on the reference blocks for sensitivity and proper functioning before resuming test.

DISTANCE-AMPLITUDE COMPARISON BLOCKS:

Hitt Blocks:

Ultrasonic Standard Reference Blocks designed to be used for distance amplitude comparisons have a specific size flat-bottomed hole placed at varying depths below the surface of the material. The three sets have 3/64″, 5/64″, or 8/64″ size flat-bottomed holes. The metal distance of the blocks normally used varies from 1/16″ to 6.0″ (see Fig. 60).

Step-block:

Calibration of ultrasonic thickness measurement equipment may be accomplished by using a "step-block". For exact calibration, it is always best to have a block whose thickness will give five signals on the screen for the range selected (see Fig. 61).

AREA-AMPLITUDE COMPARISON BLOCKS (ALCOA BLOCKS):

A set consists of eight Ultrasonic Standard Reference Blocks. Each set contains one block with the following flat-bottomed holes: 1/64″, 2/64″, 3/64″, 4/64″, 5/64″, 6/64″, 7/64″, and 8/64″. The holes are placed at a depth of 3.0″ below the surface of the material. Area amplitude relationships at the 3-inch metal distance are obtained by intercomparison of the blocks within the set (see Fig. 62).

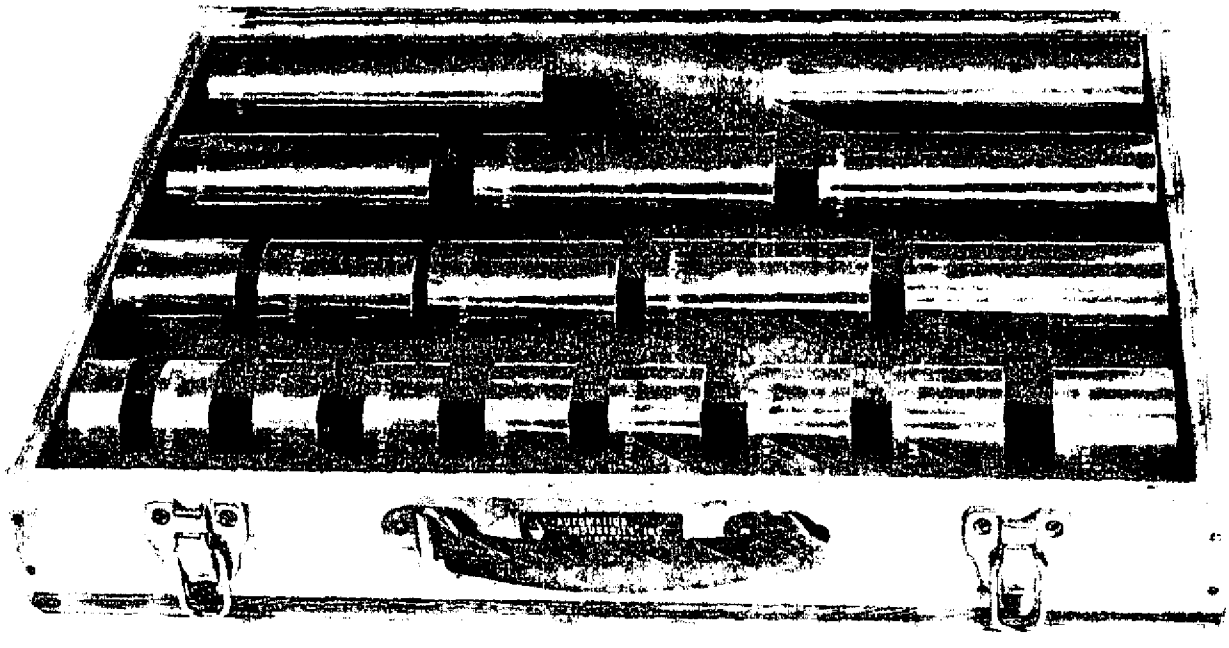


FIGURE 60. Distance-amplitude comparison reference blocks.

I.I.W. WELDING BLOCK:

The I.I.W. Welding block was developed through the International Institute of Welding (IIW/IIS) as described according to a Dutch proposal. The block has gained wide acceptance as a reference standard in distance calibration and in the calibration of the angle of sound beam propagation from angle-beam search units (see Fig. 63).

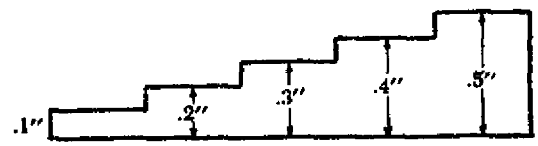


FIGURE 61. Step block.

ASME WELD REFERENCE PLATE:

This standard ultrasonic reference plate is required to check the performance and sensitivity of the ultrasonic equipment and ultrasonic search units used in the inspection of welded joints under the ASME code requirements. This block provides three reproducible levels of instrument sensitivity for both longitudinal- and shear-wave inspections and insures re-examination at the same level of sensitivity (see Fig. 64).

SPECIAL REFERENCE STANDARDS:

Many applications in ultrasonic inspections require special reference standards or blocks. The application may involve the use of standard sizes of blocks but employing a special type material or it may involve the use of special shaped blocks. A convex or concave entry surface as applicable is required when the test specimen has a curved entry surface. Many users of ultrasonic equipment prepare special reference blocks from a sample of the material under test that contains a known defect to represent the standard that is acceptable.

TESTING METHODS

Contact and immersion are the two basic methods used for ultrasonic nondestructive inspection. The instrumentation of one method can be adapted, in a limited way, to the other.

CONTACT TESTING METHOD:

The equipment used to conduct this method of inspection is designed for field use and other applications where it is desirable to bring the testing apparatus to the work (see Figs. 65, 66, 67). Figure 68 illustrates the principle of contact testing and Figs. 69 and 70 illustrate two representative portable ultrasonic flaw detectors currently available.

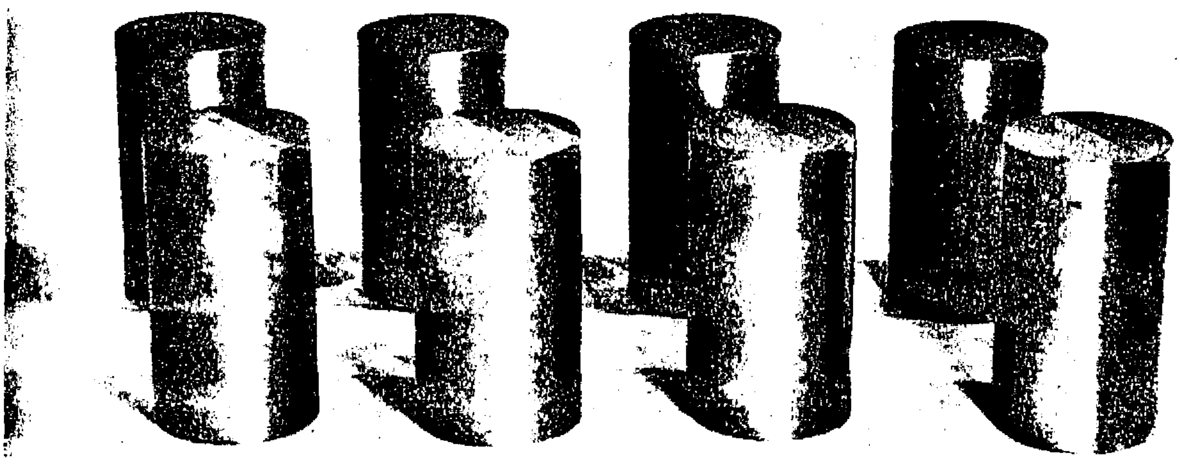


FIGURE 62. Area-amplitude comparison blocks.

Scanning of the test specimen is accomplished by manually moving the search unit over the test surface. A couplant, such as oil, is required between the face of the probe and the entrant surface of the specimen to exclude the air gap. Contact testing is normally employed for quick checks of small numbers of pieces, for examination of parts that cannot be immersed, for high resolution using twin transducers, and for shear- and surface-wave testing.

FIGURE 63. I.I.W. weld block.

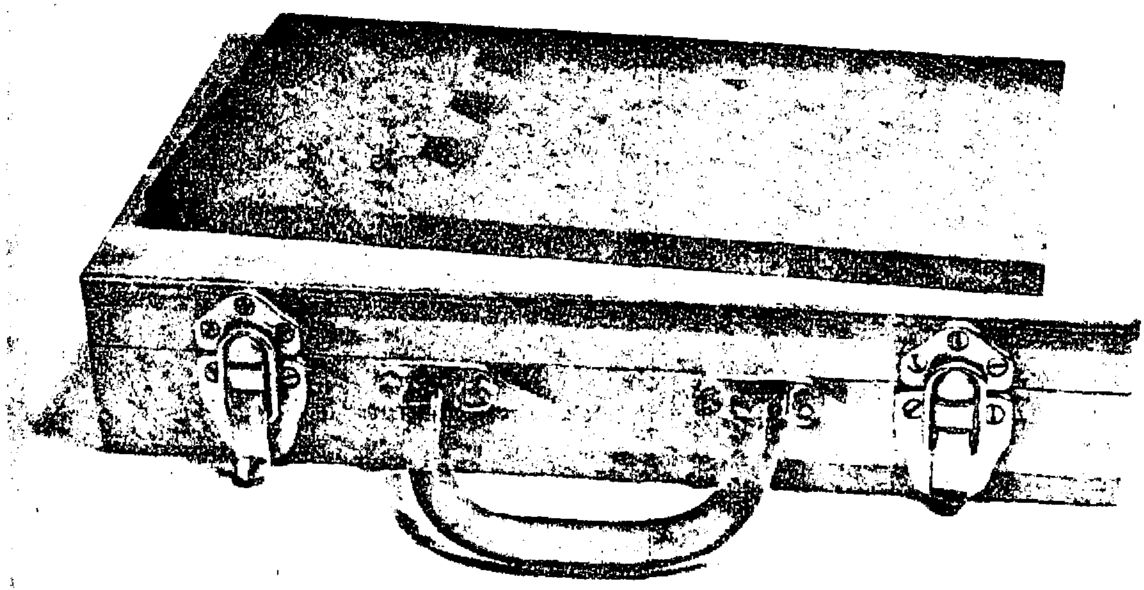


FIGURE 64. ASME weld reference plate.

FIGURE 65. Contact angle-beam test into hidden weld region of an aircraft landing gear oleo strut.

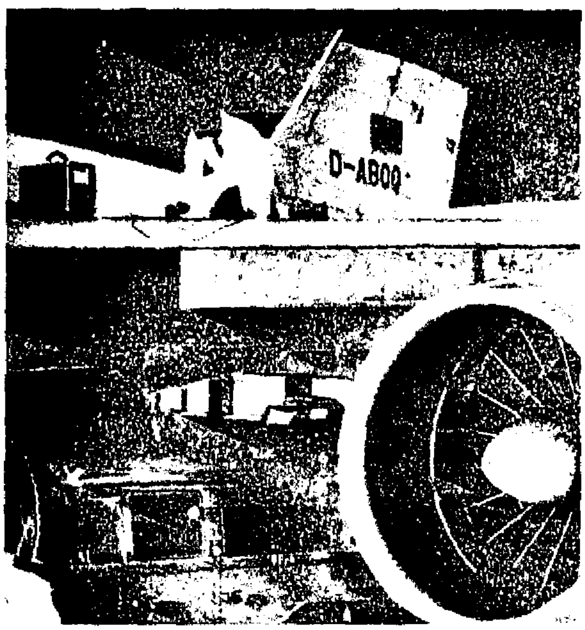


FIGURE 66. Ultrasonic inspection of a wing front spar.

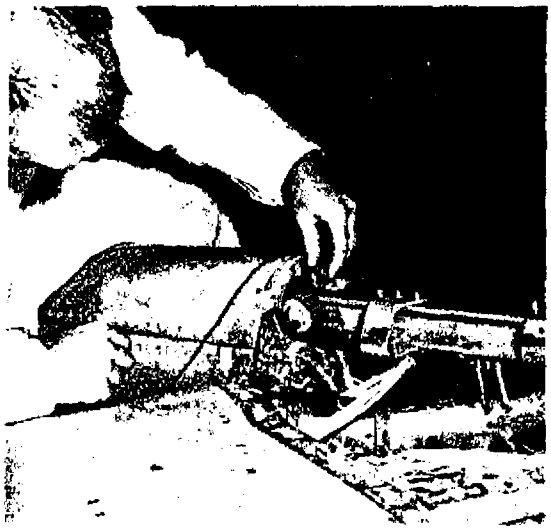


FIGURE 67. Ultrasonic inspection of a pylon structural member.

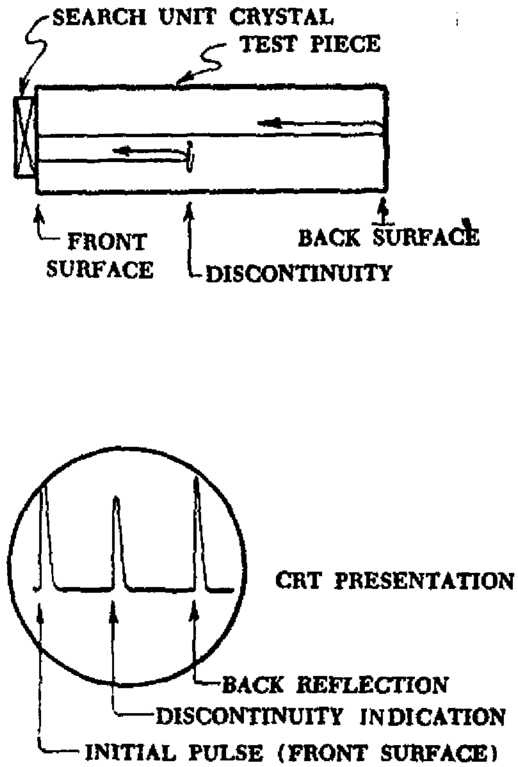


FIGURE 68. Principle of ultrasonic testing (contact).

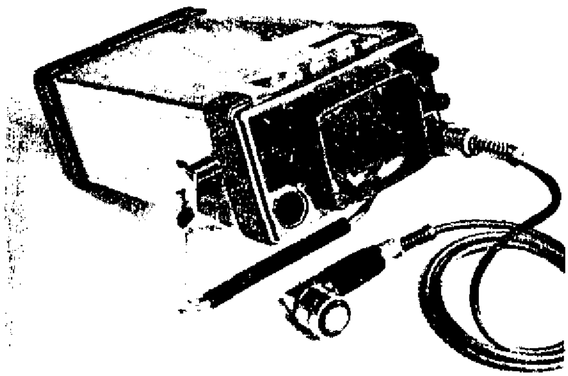


FIGURE 69. Ultrasonic miniature flaw detector.

FEATURES: (Fig. 69)

WEIGHT: Including Battery and built in Monitor 11 lbs. DIMENSIONS: 7" wide × 4½" high × 15" long. FREQUENCY RANGE: 0.4 through 12.0 mc. db calibrated gain control. One inch scale expansion, sweep delay. Testing Range, to 100" (steel). Ten hour, quick plug-in, rechargeable battery. Battery condition indication. Automatic instrument shut-off, when battery is low. Two-position "Pulse Energy" control. Easily changeable screen scale.

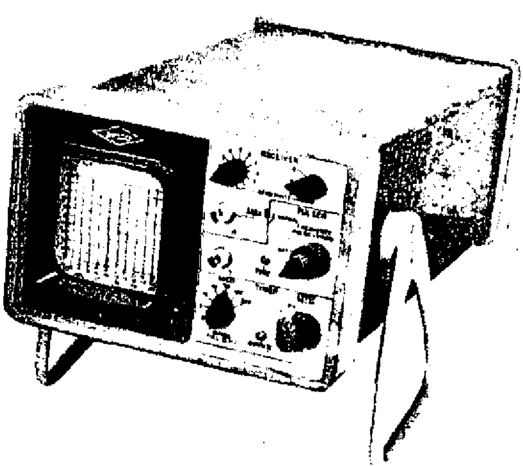


FIGURE 70. Ultrasonic miniature flaw detector.

FEATURES: (Fig. 70)

Test Frequencies: 1.0, 2.25, 5.0 mc. Size: Width 8", depth 16", height 5¼". Weight: 15 lbs. (complete with self-contained battery charger). Power Requirements: Self-contained batteries or 115V AC 50/60 cycles. Capable of 8 hours continuous operation on batteries. Sensitivity: Using 5.0 mc. test range, the reflection from a 1/64" hole in an Alcoa "A" test block is 2¼" high (full scale). Resolution: Using 5.0 mc. test range, the reflection from a 5/64" hole ⅛ inch from the surface is clearly resolved. Linearity: Size of signal is proportional to size of reflecting area within the signal amplitude range up to 2¼". Dynamic Range: The dynamic range is better than 64:1. With controls set to produce a clearly defined signal from a No. 1 Alcoa "A" block, the signal from a No. 8 block is below full-scale deflection. Display Range: From 1" full screen width to 20'. Ambient Range: 0°–120°F.

IMMERSION TESTING METHOD:

Immersion testing is superior to contact testing in the following respects:

1. High-speed, repetitive inspections may be conducted using a pre-programmed fully automated system.

2. Forgings, castings, and nonsymmetrical parts with fillets, rough surfaces, radii, etc., that cannot be tested by the contact method may be immersion tested with a manually operated scanning system.

This method of inspection is accomplished by:

1. Immersing both the search unit and the material in a liquid couplant, normally water (see Fig. 71).

2. By a squirter or bubbler which directs a column of flowing water to form a couplant between the face of the transducer and the surface of the specimen (see Fig. 72).

3. By a wheel-search unit in which the transducer is mounted in a liquid-filled tire. The tire is operated in direct contact with the material (see Fig. 73).

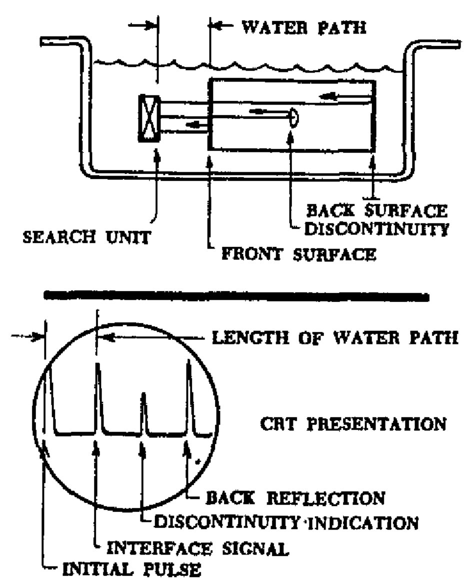


FIGURE 71. Principle of ultrasonic testing (immersion).

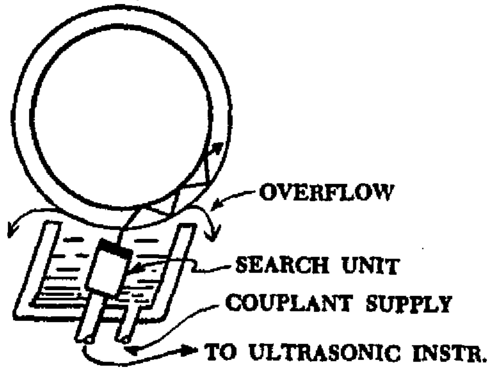


FIGURE 72. Bubbler angle-beam testing (pipe).

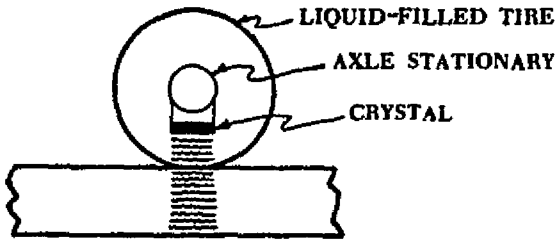


FIGURE 73. Wheel scanning method.

A description of the three techniques follows:

Immersed Scanning Technique:

Both the search unit and the part to be tested are totally immersed in water. The sound beam is directed into the material normally by a straight-beam search unit. Angle-beam techniques such as shear, surface, or plate waves are accomplished through control and direction of the sound beam (see Figs. 74, 75, and 76).

In immersion testing by the straight-beam technique, the water path distance (search unit to front surface of the test piece) is generally set longer in time than the length of scan (front surface to back surface) so that the first multiple of the interface signal will appear further along the CRT sweep than the back reflection. This is done to clear the test area of signals which may cause misinterpretations. This is particularly important when the test area is gated for automatic signalling and recording operations (see Fig. 77). Velocity in water is approximately $\frac{1}{4}$ that of aluminum or steel; therefore, 1″ of water path will appear on the screen presentation as equal to 4″ of

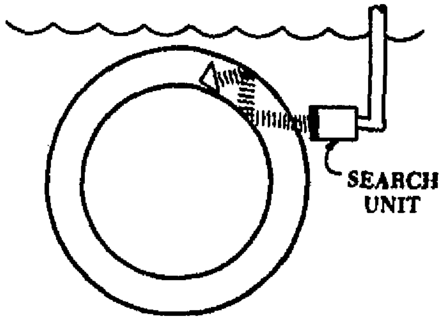


FIGURE 74. Immersed angle-beam technique (pipe or tube).

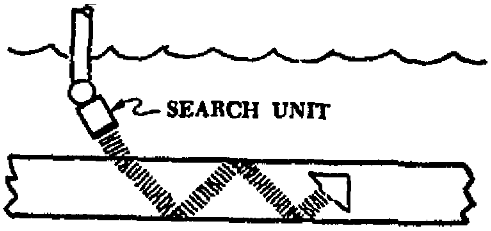


FIGURE 75. Immersed angle-beam technique (plate or sheet).

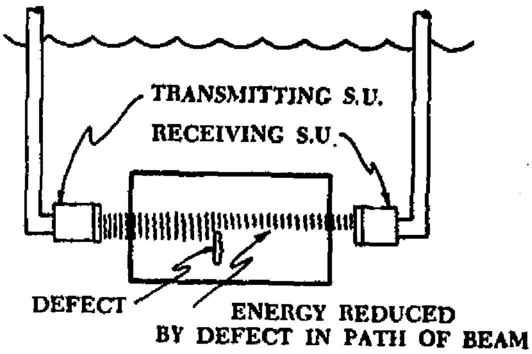


FIGURE 76. Immersed through-transmission technique.

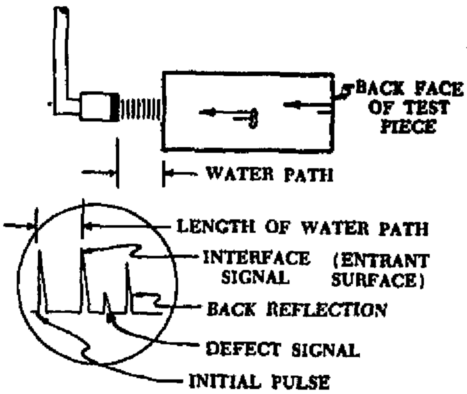


FIGURE 77. Removing first multiple of interface indication from test area.

steel. Hence, a rule of thumb for water-to-part distance is ¼ thickness of part plus ¼″.

Focused Search Unit Technique:

The high-frequency mechanical vibrations of the sound beam can be focused through acoustic lens structures in a manner similar to that achieved by glass lenses in optics. The acoustic lens is an integral of the focused search unit assembly and is designed to provide a well-defined and directed sound beam pattern. The energy propagated from the search unit can be concentrated through spherical lens structure into cone-shaped beams with high intensity (see Fig. 78). Through cylindrical lens structures, the sound energy can be contoured into a wedge of sound-beam energy. Spherically focused systems are used in special inspections which require an intense, well-defined sound beam. Cylindrical lens structures are used for contour correction in longitudinal- and shear-wave inspection of cylindrical parts. Focused search units allow the best possible resolving power and the highest flaw definition with standard ultrasonic equipment.

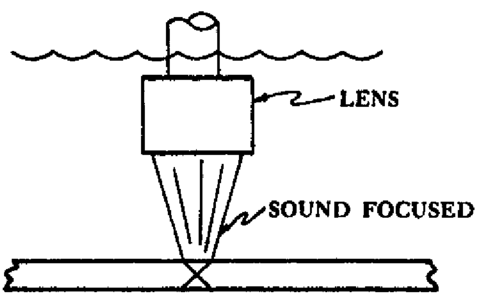


FIGURE 78. Focused search unit.

Beam Collimator:

Beam divergence varies with frequency and crystal diameter. The higher frequencies give more directivity to the sound beam and a 1″ diameter crystal at any frequency is more directive than a ½″ diameter crystal operating at the same frequency. Therefore, to obtain more directivity (which results in a better definition of the defect) the frequency must be increased or a larger diameter crystal must be used.

Increasing the frequency to obtain a better definition of the defect often defeats the purpose of the test, since the increase in frequency is also an increase in sensitivity. The higher sensitivity discloses irrelevant factors such as surface scratches, nicks, and dents which make the defect evaluation difficult.

Therefore, to obtain more directivity of the sound beam without increasing the frequency, a larger diameter crystal is used. Since the defect under examination may occupy only a small portion of the total area of the beam spread, a beam collimator is used to reduce the area of the sound beam entering the test piece to cover only the area under inspection.

The sound-carrying shaft in the center of the collimator conducts the straight center rays of the transducer into the specimen. The remainder of the beam is prevented from reaching the test piece or returning a signal to the transducer by the acoustical block (see Fig. 79).

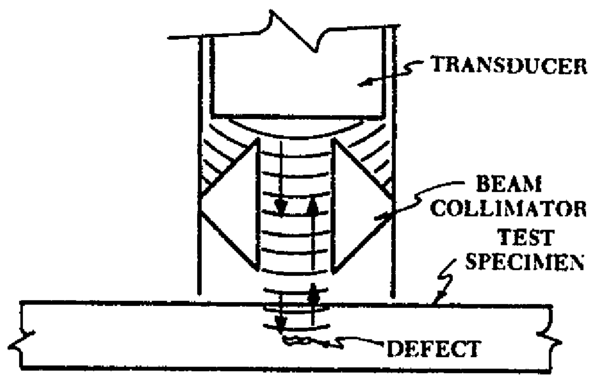


FIGURE 79. Beam collimator.

Collimated beams usually result in a better definition of the defect; however, there are also certain disadvantages which must be considered when using this device. Collimating the propagated beam decreases the incident energy reaching the test piece. This reduction in the total useful sound energy limits the maximum material thickness that can be inspected. Also alignment becomes critical since the diameter of the collimator beam is small (normally 1/16″ to 3/8″) in comparison to the total area of the transducer.

Water Column Technique (Bubbler, Squirter):

The water column scanning technique operates on the immersion principle where a beam of high-frequency sound is projected through a water path into the test material. This technique is adapted to high-speed scanning of plate, sheet, strip, cylindrical forms and other regularly shaped parts. The sound beam is projected into the material through a column of flowing water. The sound beam can be directed into the material either perpendicular to the test surface (Fig. 80) or at an angle (Fig. 81).

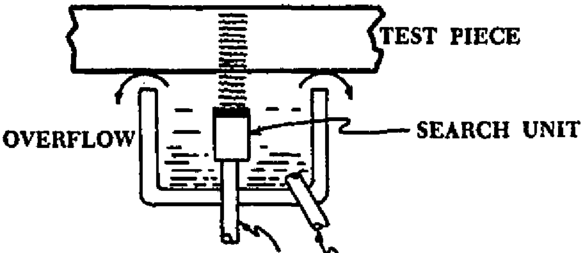


FIGURE 80. Bubbler scanning method.

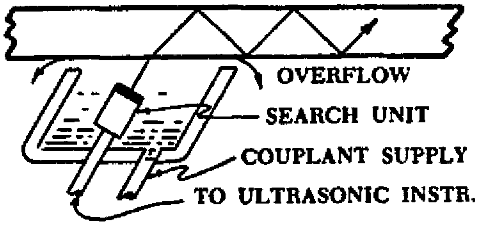


FIGURE 81. Bubbler angle-beam technique (plate.)

Wheel Search Unit:

The wheel search unit operates on the immersion principle in that a beam of high-frequency sound is projected through a liquid path into the test material. The search unit, mounted on the axle of a wheel with a liquid-filled rubber tire, is held in a fixed position relative to the test surface while the wheel rotates freely. The wheel search unit may be mounted on a stationary fixture, in which case the material moves past it (see Fig. 82) or it may be mounted on a mobile fixture which runs over the material (see Fig. 83).

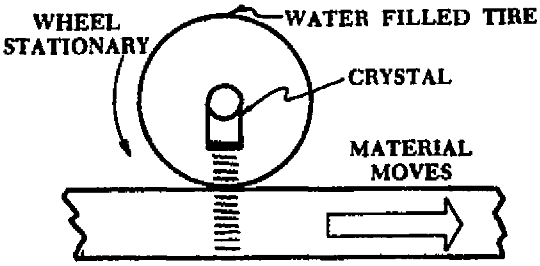


FIGURE 82. Wheel search unit in fixed position.

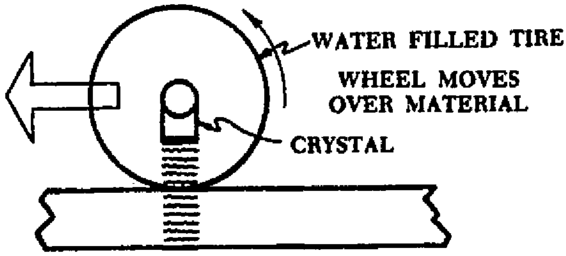


FIGURE 83. Wheel search unit moves over the material.

The wheel is used in a wide variety of applications, and is especially useful for high-speed automated ultrasonic flaw detection systems since it combines advantages of both contact and immersion testing methods. The wheel eliminates the need for immersion tanks by coupling the transducer to the specimen through a water path and the resilient material of the tire-shaped casing.

Rusty, scaled, pitted, rough machined and as-forged surfaces are successfully scanned with the wheel search unit.

The position and angle of the crystal mounting on the axle are determined by the test method and technique to be used, i.e., straight beam or angle beam.

Ultrasonic Image Converter:

The ultrasonic image converter is an evacuated tube having a piezoelectric quartz window, and contains an electron gun and multiplier (see Fig. 84). When ultrasonic energy is impressed upon the quartz window, a piezoelectric voltage is produced whose magnitude at any one point corresponds approximately to the ultrasonic intensity at that point. These voltage variations influence the secondary emission generated by the scanning electron beam. The produced signal is then amplified and displayed using conventional closed-circuit television techniques.

Acoustic impedances, which are defined as the product of the density and velocity of a material, are matched in the ultrasonic image converter unit by means of transition layers. These layers accomplish two major functions: First, they allow a maximum transfer of energy from the couplant to the quartz receiving crystal by reducing the amount of energy reflected; and, second, they eliminate in part some of the standing waves so common with continuous wave systems. The transition layers are constructed of epoxy and tungsten powder, and cemented directly to the quartz receiving crystal. In addition, an "interference depressor" (a rubber diaphragm attached to the receiving crystal) is used to further eliminate the problem of standing waves. Standing waves are the result of energy reflecting back and forth between the receiving crystal and the test object since it is impossible in actual practice to match all impedances in a system so that no reflections occur.

Since high-frequency crystals (5 to 10 mc.) are extremely thin, they present a supporting problem. A grid which acts both as a support plate for the crystal and as a direct reference by which flaw size can be measured is built as an integral part of the face plate assembly for the demountable tube system. A similar device may also be incorporated into the sealed tube system for high-frequency operations.

Flaw detection is based on the fact that when a discontinuity is present in a material, there will exist a difference in acoustic impedances. This impedance difference will normally cause attenuation of the sound energy by reflecting a portion of the energy back toward the source. Flaws are thus presented on the TV monitor as black areas, denoting a relatively low sound intensity field. The surrounding matrix will usually be presented as a relatively uniform grey to white field, denoting high sound intensity. A through method of transmission is normally used with longitudinal waves. Shear, surface, and plate waves may be employed in special cases by using a combination of the contact and immersion techniques. This method of test is used in detecting surface, near-surface, and deep-seated flaws when access to both faces of the specimen is possible. When only one surface is accessible, then reflection techniques are employed. The reflection test method is used for surfaces and near-surface testing involving cracks and nonbonds.

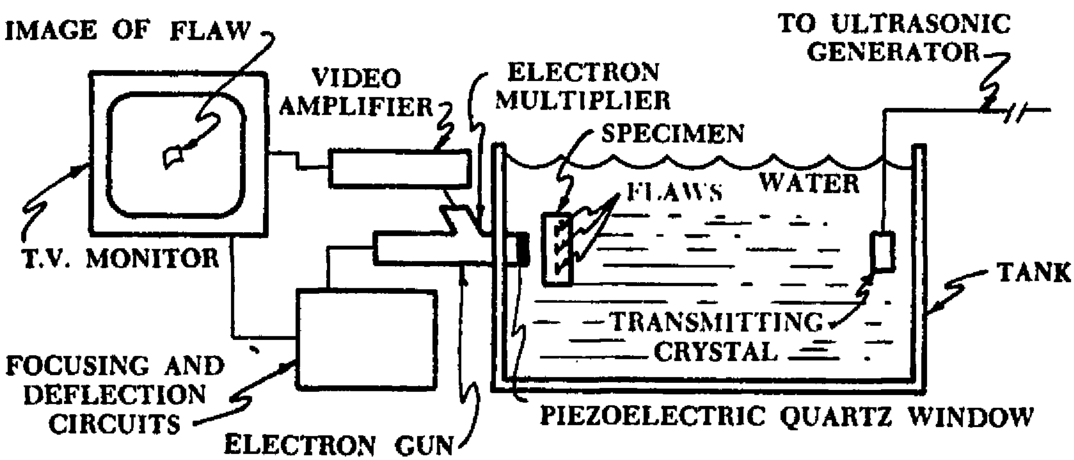


FIGURE 84. Schematic—ultrasonic image converter system.

Equipment Requirements:

Immersion system (see Fig. 85):

The basic units of an immersion testing system consist of a test tank, bridge and carriage, manipulator, search tube and transducer, and display/recorder.

1. Test Tank:

The tanks vary in size to meet specific requirements and are normally fitted for a high-volume, low-pressure water filter system for recirculation of tank water.

2. Bridge and Carriage (See Fig. 86):

Provides a means of positioning and moving the search unit over the specimen. The bridge unit travels along the length of the tank, while the carriage, which is mounted on the bridge unit, travels along the length of the bridge.

3. Manipulator, Search Tube and Transducer (see Fig. 87):

The transducer is positioned below water level by the search tube which in turn is positioned by the manipulator. The manipulator is mounted on the carriage and provides vertical travel, rotation in azimuth and angular displacement of the probe.

4. Display/Recorder (see Fig. 88):

The ultrasonic test unit transmits and receives signals from the transducer, and amplifies these signals for presentation on the CRT or recorder.

Automatic Testing Systems (see Fig. 89):

A typical automatic scanning system includes:

1. The electronic console containing the CRT and controlling circuits. Adjustable circuits are provided for picking off the reflections from discontinuities within specified areas and discriminating as to amplitude for recording or signaling alarm purposes.

2. Automatic scanning bridge with programmed drives and controls.

3. Manipulator, search tube, and transducers.

4. Recorder and recorder adapter.

5. Test tank.

6. Turntables and rotators (see Figs. 90 and 91).

7. Material handling system.

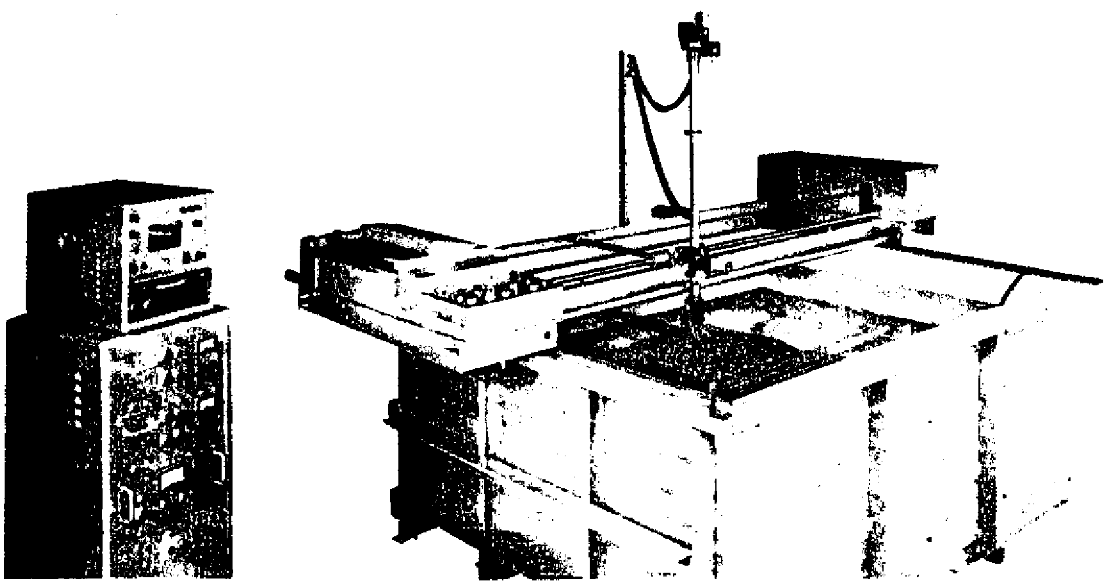


FIGURE 85. Ultrasonic immersion testing system.

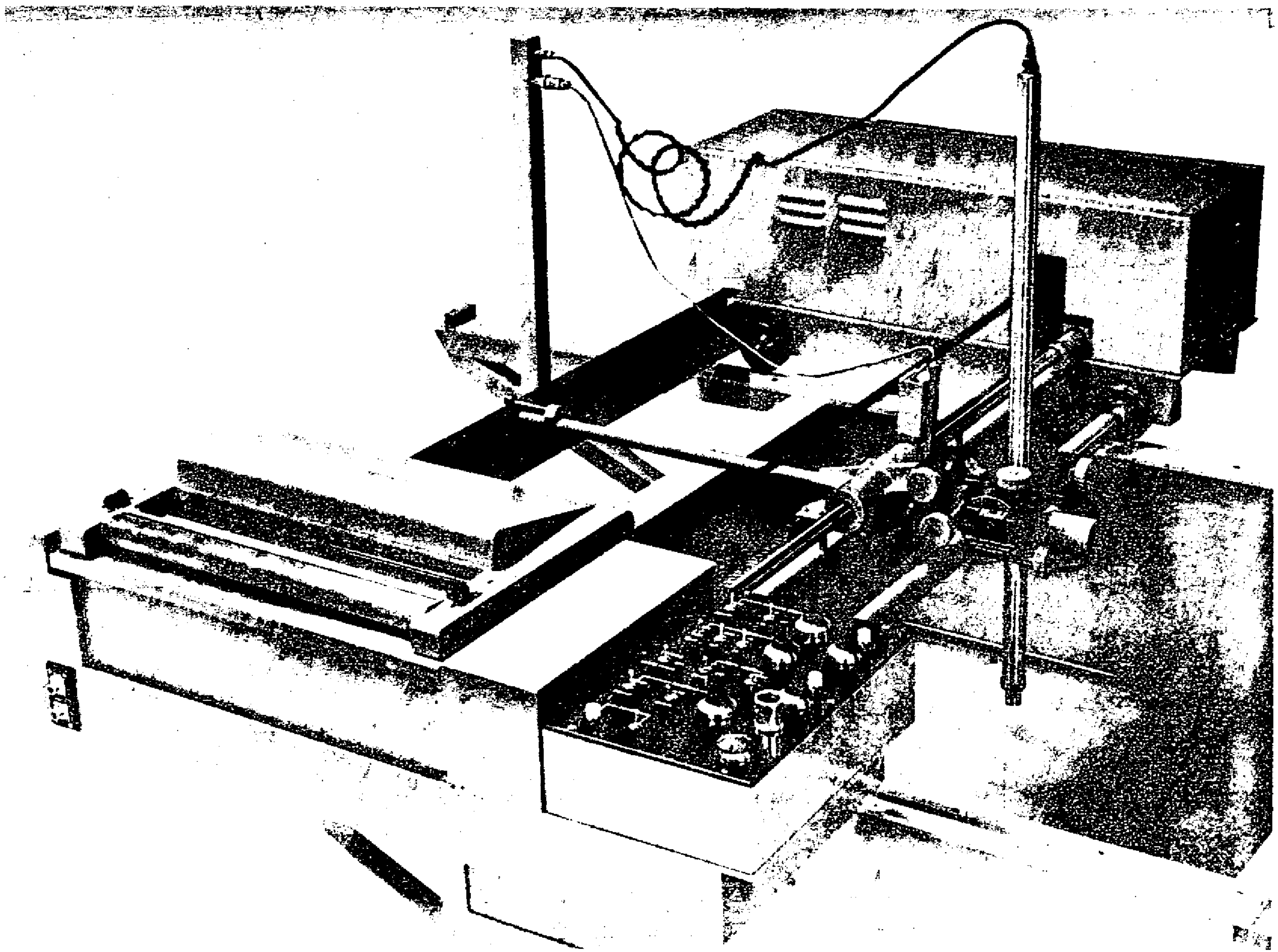


FIGURE 86. Bridge and carriage.

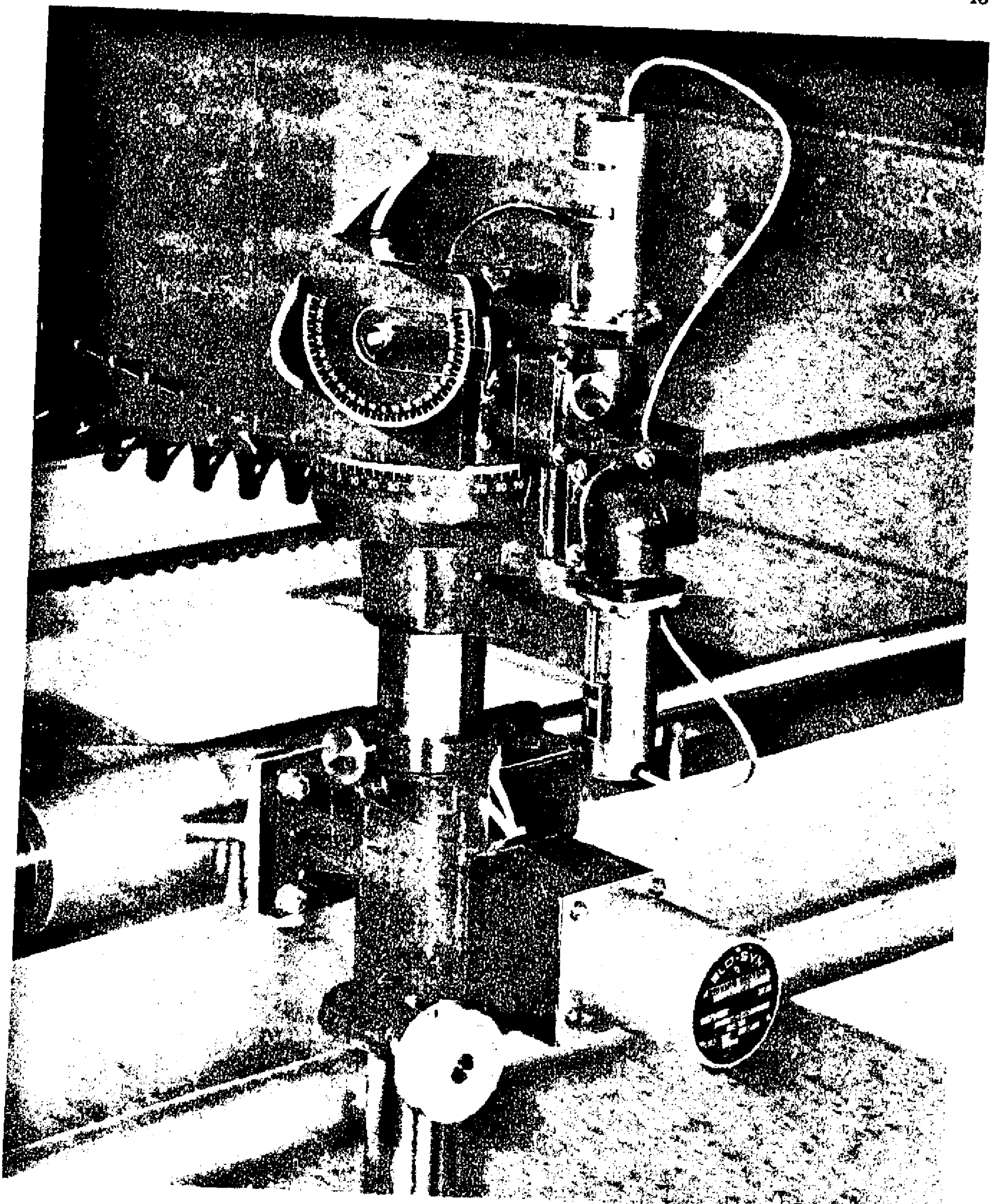


FIGURE 87a. Manipulator, search tube, and transducer. (upper view)

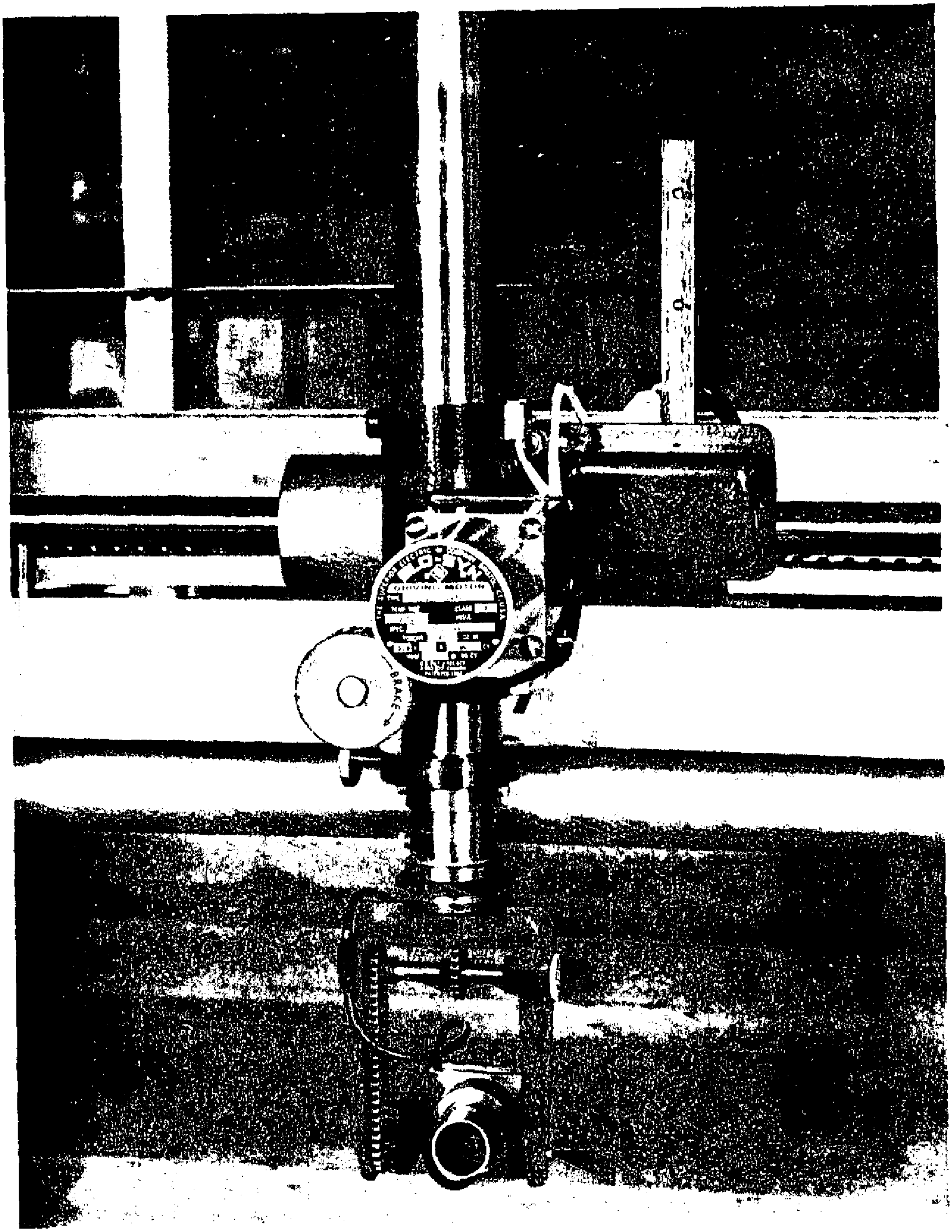


FIGURE 87b. Manipulator, search tube, and transducer (lower view).

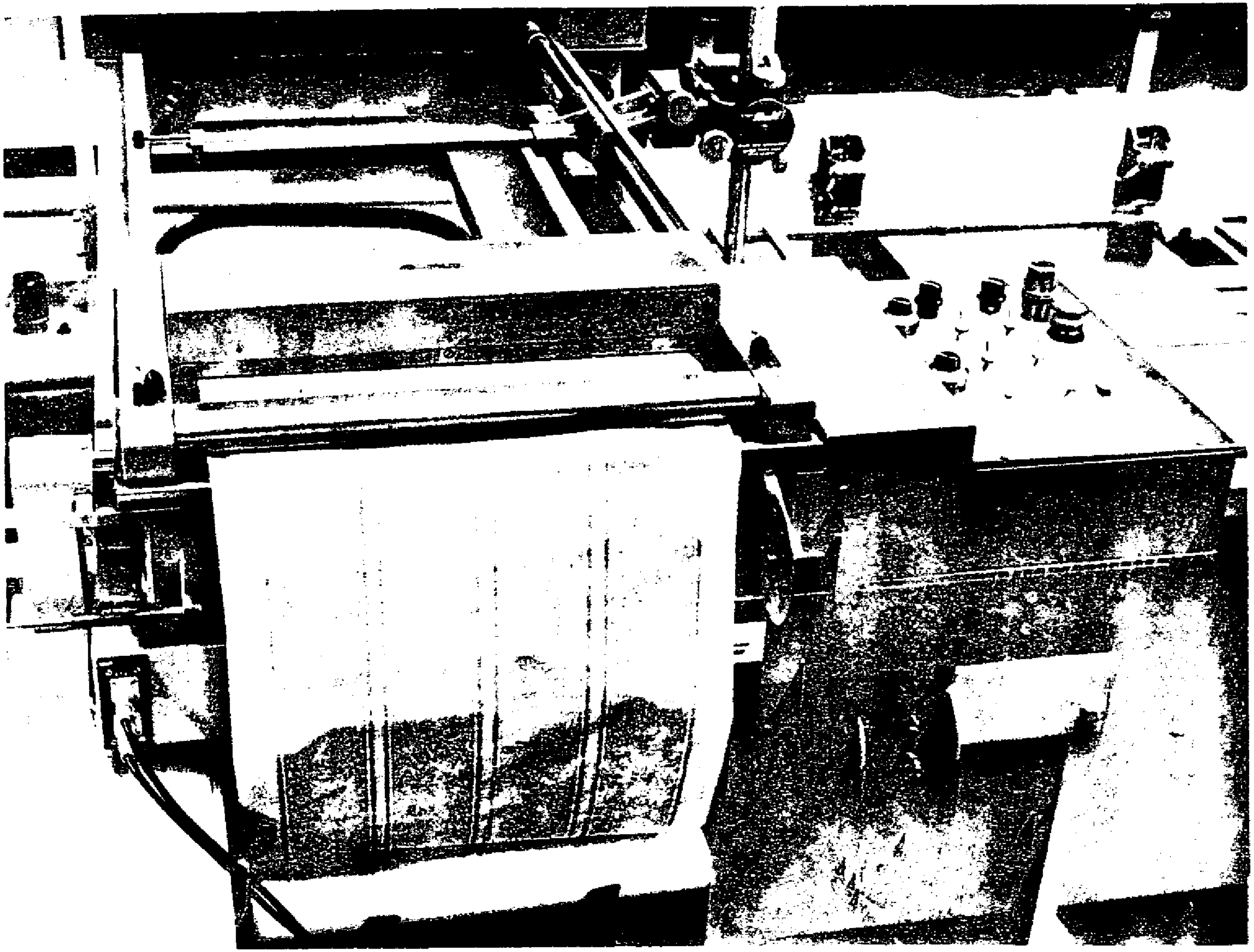


FIGURE 88. Facsimile recorder.

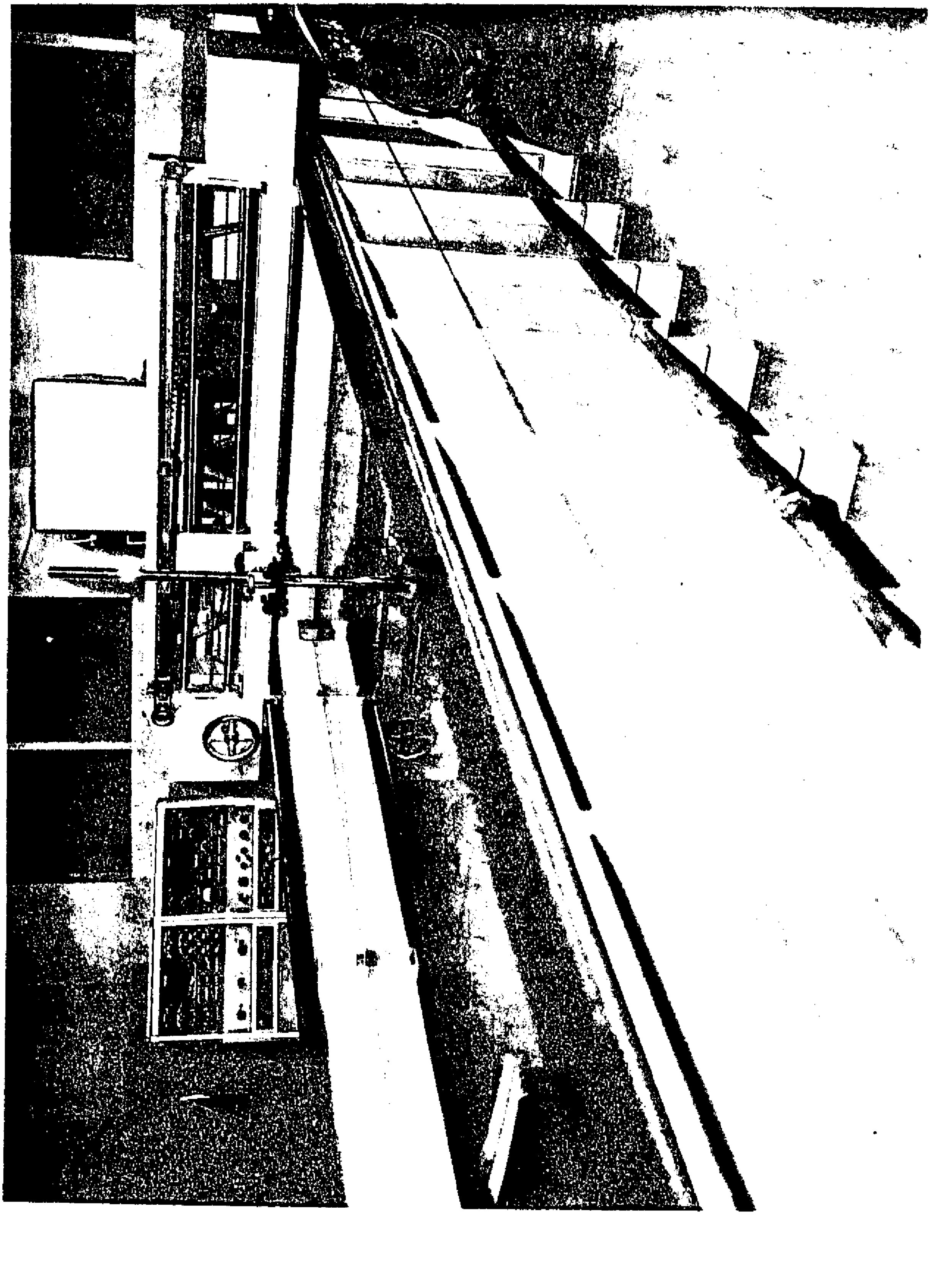


FIGURE 89. Automatic scanning system.

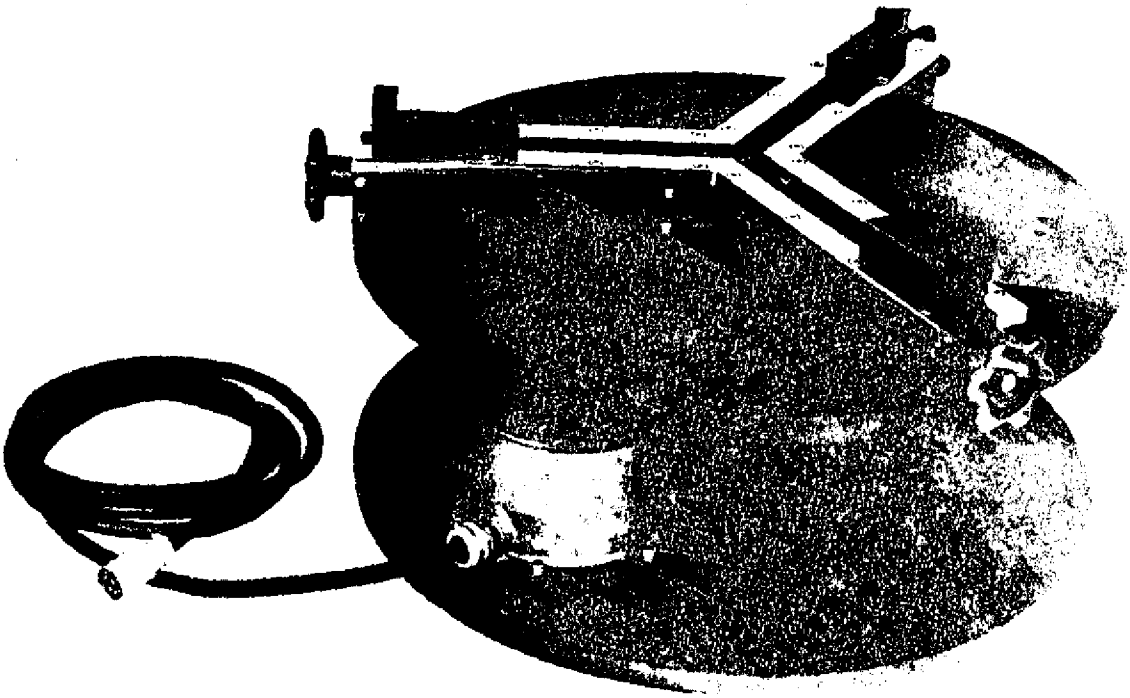


FIGURE 90. Immersible rotating turntable.

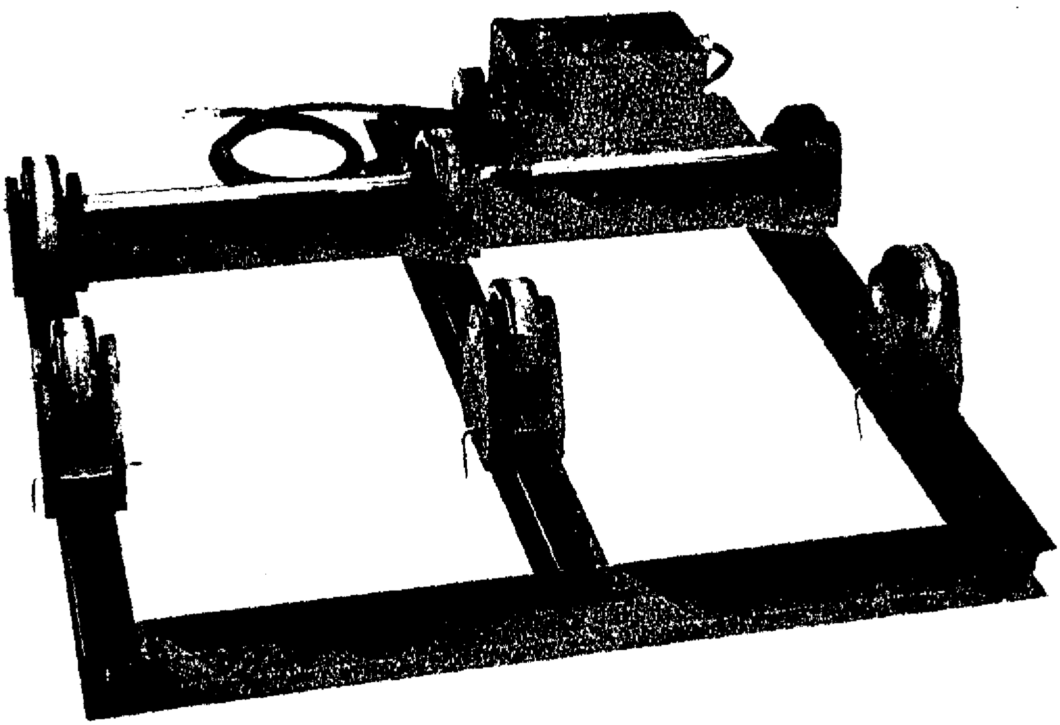


FIGURE 91. Immersible indexing fixture.

In addition, an automatic system will normally have go/no-go monitors, defect markers (paint-spray or grinding wheel), defective material sorters, and visual or aural alarms.

A bubbler or squirter testing system or a wheel search unit may be used in place of items 3 and 5.

The equipment must be rigidly constructed in order to duplicate a test since positioning of the search unit with respect to the surface of the test piece is extremely important. Nonrigid supports and backlash in the search unit controls can completely upset a test, as a change of 1° in the angle of the search unit will change the refracted angle in the material over 2° at small angles and up to 7° at large angles.

Automatic scanning is used where repetitive inspections are conducted on pieces of the same size, shape, and material. A monitor eliminates the human element of unintentionally neglecting to observe all defects, and automatic scanning assures that all areas of the test piece are scanned.

In any automatic scanning operation, it is essential that parallelism and distance be constantly maintained between the transducer face and the entrant surface of the specimen. Automatic systems, unless preprogrammed to compensate for these factors, will be limited to the testing of items such as plate, sheet, billets, extrusions, cylindrical forms, and other regularly shaped parts.

Preprogrammed automated testing system:

A preprogrammed system must be capable of maintaining parallelism between the crystal face and the profile of the test part regardless of part geometry. Preprogramming may be accomplished by cam, electric, air, hydraulic, or tape control. Since tape control is the most versatile, this method is used to preprogram ultrasonic testing equipment.

Punched tape control:

A scanning program of the specimen is set up which assigns a numerical value for each point to be inspected. The numerical dimensions in the form of coordinates referenced to a common axis of the test specimen are recorded on a numerical drawing. A process sheet is then made from the numerical drawing. From the information on the process sheet, a perforated tape is made on a key-punch typewriter. The process tape is then fed to a computer which automatically converts the information to a binary, two-number 0-1 code and punches the control tape.

The control tape is mounted on a photoelectric reader in the machine control unit which senses the holes in the tape. The coded digital information is changed to command pulses by the decoder. The binary numbers correspond to the number of command pulses that must be delivered to each axis in order to drive the ultrasonic scanner. Physical movement of the scanner is controlled by the command pulses through servo-motors.

The three axes of movement that must be controlled are termed X, Y, and Z and are normal to each other. In addition, there are axes of rotation about the Y and Z axes, making five in all (see Fig. 92). To facilitate the movement of the scanner, all dimensions assigned are in the form of coordinates referenced to a common axis of the test piece.

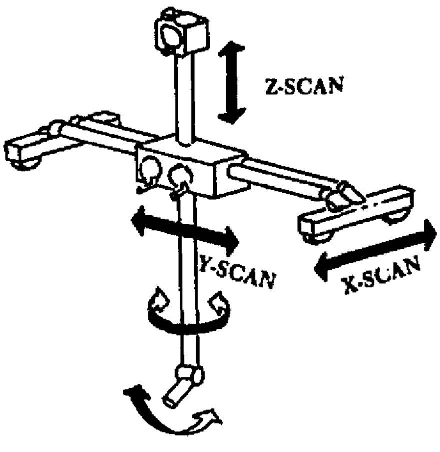


FIGURE 92. Scanning bridge and probe positioner.

There are two types of numerical control systems, point-to-point and continuous path. The point-to-point method moves the scanner on the X and Y coordinates to a desired position and provides a high degree of accuracy as to location of the coordinates, but no restrictions are placed on the path the search unit takes in achieving the location. The point-to-point system is the most commonly used since the process sheet may be worked out by a human programmer.

Continuous path or contouring is much more complicated than the point-to-point system. In contouring, the transducer path may be for any shape, i.e., a parabola, arc, sphere, square, or any combination of these in three dimensions. Since the entire path of the transducer must be described by the data input medium in addition to other functions such as beam angle, depth of scan, sensitivity, etc., a computer is required. The complex problem of calculating the thousands of points needed to position the search unit for continuous-path control is not practical to solve except with a computer.

Figure 93 illustrates a tape-controlled system produced by the Budd Company to ultrasonically inspect large bulkheads (pressure vessel endcaps, 33′ in diameter) used on the Saturn stage II fuel tankage. The walls of the bulkhead are of honeycomb structure, so the bond between case and skin must be perfect and the core must be undamaged.

The through-transmission technique is used; only the boom carrying the outside transducer track is visible. However, another transducer is positioned inside in precise relationship with the outside transducer. The transducers are mounted on horizontal movable arms which, in turn, rest on vertical columns that also move. The transducers themselves can be moved somewhat like fingers to change the angle of the sound beam. The outer and inner transducers contain water jets to provide acoustic coupling with the bulkhead. A movable platform rotates the bulkhead. All these motions are synchronized by means of tape programs so that many scanning schedules can be tried. Readout is accomplished by a stylus that tracks on special electrosensitive paper mounted on the surface

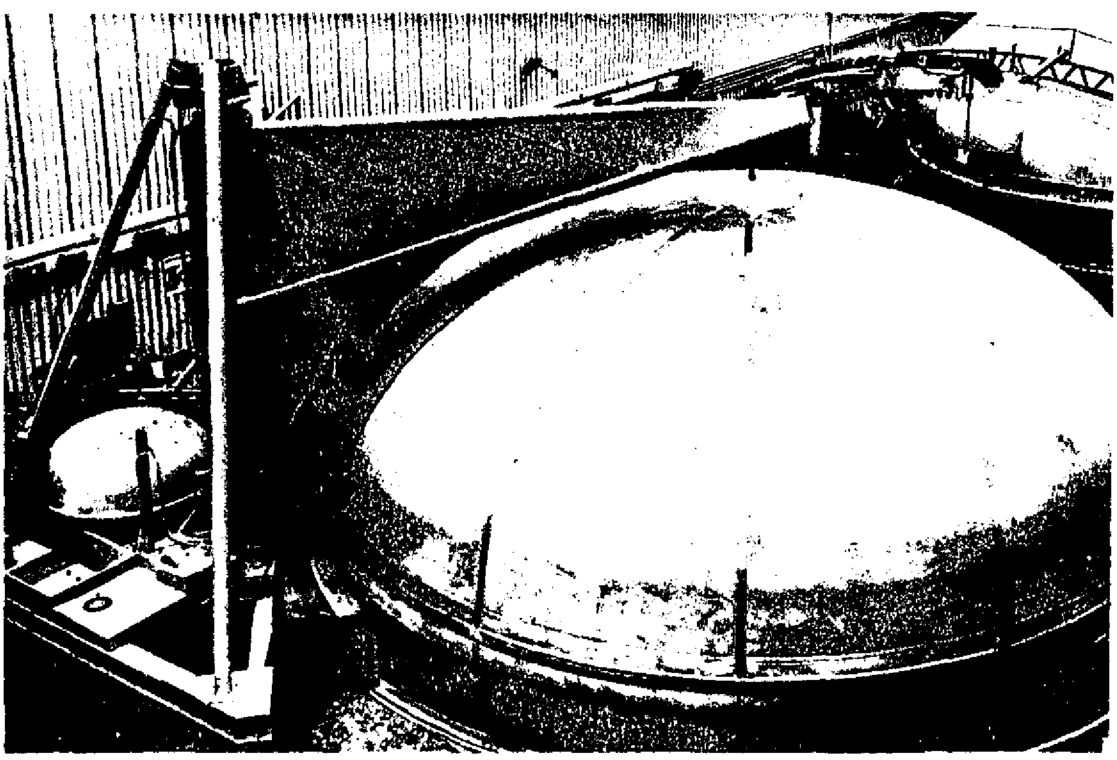


FIGURE 93. Ultrasonic inspection system used to inspect Saturn stage II bulkhead.

of the scale model (shown at the left of the test article in Fig. 93) whose motion is synchronized with that of the actual bulkhead.

TESTING TECHNIQUES (Welds)

The objective in ultrasonic inspection is to transmit a beam of sound into the material under test at a chosen point, to direct it as required, and study its behavior within the material by means of suitable detection techniques. This must be done in such a way that the existence of shadow zones, boundary and flaw echoes, and anomalous scatter and absorption can be analyzed from the ultrasonic response patterns.

TESTING WELDED SEAMS:

Welds are normally inspected with the use of shear waves and the *golden rule of ultrasonics* should always be followed. That is, direct the sound beam to hit all flaws at, or as close to, a right angle as possible.

To perform accurate weld testing, the following four steps must be performed:

1. Detection of all flaws above a certain predetermined size.
2. Accurate location of the flaws.
3. Identification of the flaw type.
4. Measurement of the flaw size.

Detection of Flaws:

Practically any probe-instrument combination will indicate the presence of flaws, if the sensitivity is high enough. However, a probe of the proper angle will improve the ratio of flaw signal to the weld-zone noise that is always present. This is achieved by having the beam strike the flaws as close to 90° as possible while maintaining a short probe-to-flaw distance. For butt welds, the following angles should be used:

For welds ground on both sides:

Material thickness	*Probe angle*
up to 5/8″	80°
5/8″ to 1¼″	70°
1¼″ to 2½″	60°
2½″ upwards	45°

For crowned welds:

Material thickness	*Probe angle*
up to ¾″	80°
¾″ to 1⅝″	70°
1⅝″ upwards	60°

Accurate testing of welds cannot be performed unless the angle of the sound beam in the material is known. The wear face of the transducer will normally wear out unevenly which changes the beam angle. Prior to conducting any test, the probe should be checked and calibrated to the required accuracy.

Location of Flaws:

During testing the probe is moved as illustrated in Fig. 94 to assure the whole section of the seam has been traversed by the ultrasonic wave. The probe must be continuously turned around its vertical axis in order to pick up defects which are not parallel to the longitudinal axis of the seam.

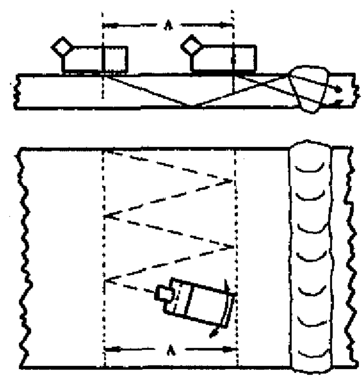


FIGURE 94. Location of flaws in weld.

Figure 95 shows the sound beam path in butt weld testing. To accurately locate flaws, the following must be known:

E—The exit point of the sound beam.

α—The exact angle of incidence of the beam.

T—The thickness of the plate.

The sweep of the instrument must be calibrated accurately in distance of the sound travel.

With this information, flaws can be located by trigonometry or by making a scale sketch. This is time consuming and a better method is to use a flaw-locating ruler that is attached to the probe.

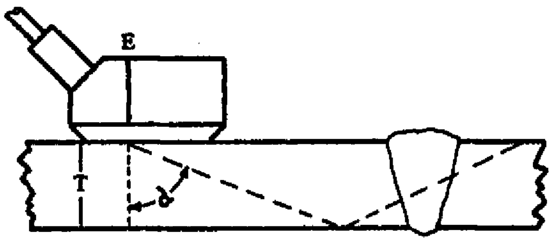


FIGURE 95. Sound beam path in a butt weld test.

Figure 96 shows how the ruler works. The bottom part of the illustration shows a section of the weld area and the position of the sound beam. The center shows a plan view of the rule. The instrument screen is shown at the top. The ruler has been adjusted so that the exit point of the sound beam coincides with the 0 point on the rule. The slider has been adjusted for the exact thickness of the plate at its intersection with the sloping line. The instrument sweep is adjusted to the calibration marks on the rule and on the screen. When a flaw echo appears, it is brought to its maximum height by moving the probe. Then its position is read off the screen and at the same calibration point of the rule the depth of the flaw on the thickness scale is read. The flaw is directly underneath the same point on the rule. This device gives the exact position of the flaw in two planes, without calculations. Its accuracy is dependent on proper adjustment with the plate thickness, exact calibration of the instrument sweep, and having a probe producing a beam at the same incidence angle as the ruler is designed for.

Identification of the Flaw Type:

Normally, the flaw echo by itself, is insufficient to identify the flaw. To obtain the information to identify the flaw type, the changes in the echo are observed with the changes in position of the probe.

1. Echoes from single pores or spherical flaws will be the same for all probe positions (see Fig. 97).
2. Echoes from laminar flaws will decrease rapidly when probed at angles less than 90° to the direction of the weld (see Fig. 97).
3. When the decrease in the height of the echo is the same for the same decrease in angle from 90°, the flaw is parallel to the seam. In the case of cracks, different size echoes will be obtained due to small variations in the crack orientation.
4. Probing from both sides of the weld and noting the relative echo size and shape will establish two angular deviations from the vertical (see Fig. 98).

Measurement of Flaw Size:

The size of flaws which are smaller than the sound beam is determined by comparison of the flaw echo with an echo obtained from a reference plate that contains drilled holes or slots of known dimensions. The comparison must be made at a lower amplification than is necessary for the rapid detection of flaws. The instrument should be capable of being switched down to accurate reproducible gain settings. The size of flaws which are larger than the sound beam is determined by outlining the flaw by the "go-around" method, i.e., by moving the transducer around the periphery of the flaw.

FILLET WELDS:

Although fillet welds are being inspected by ultrasonics, it is the opinion of many specialists in this field that such welds cannot be tested accurately. Therefore, a thorough investigation of the test methods and results should be conducted when manufacturers elect to use ultrasonics for this purpose.

RESISTANCE WELDS:

Ultrasonic testing of spot welds on a production basis until recently was not considered practical. Delay lines to increase resolution power provide one means of investigating or evaluating "close-to-surface" defects, such as those found in spot welds. However, for "on-line" manufacturing applications the ultrasonic image conversion systems are more suitable.

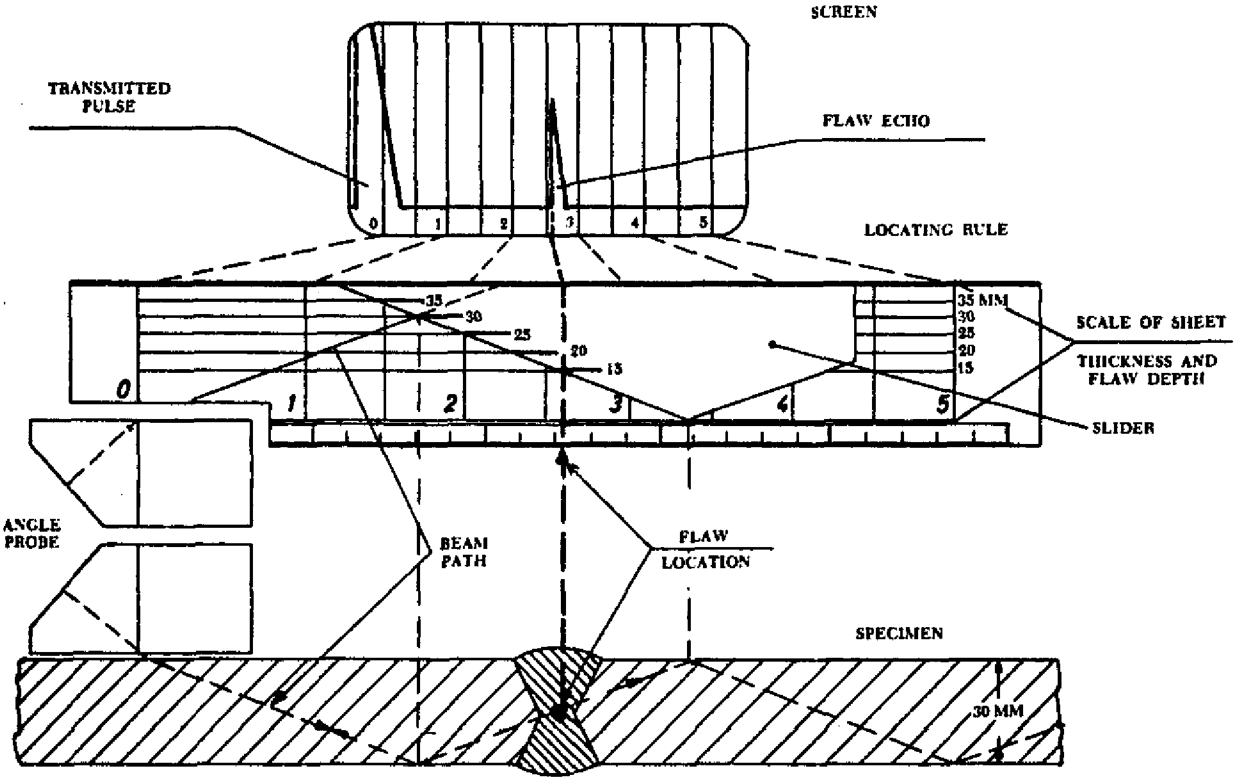


FIGURE 96. Diagram to show the method of using a flaw-locating rule.

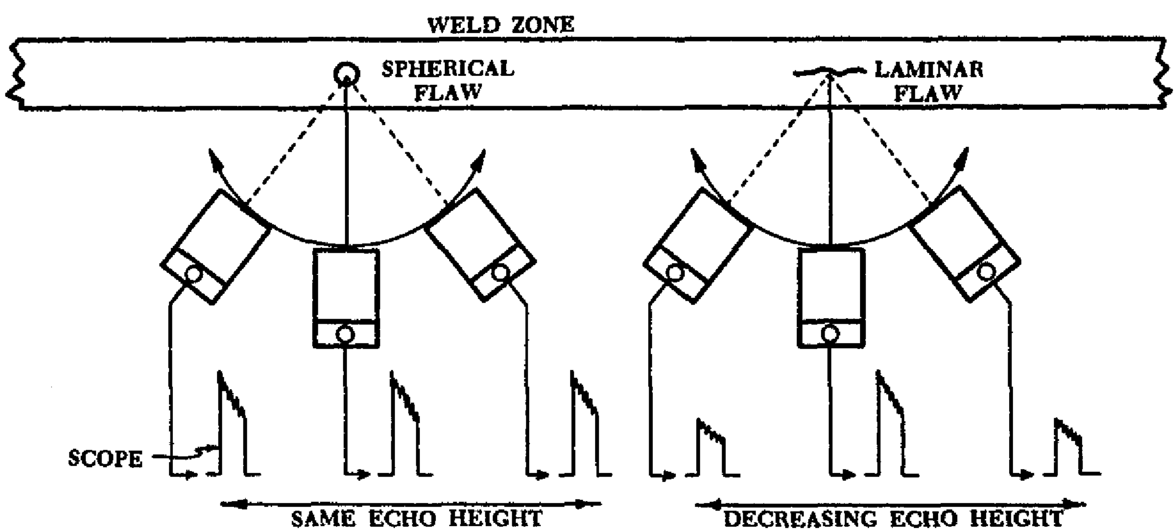


FIGURE 97. Identification of flaw-types by echo height.

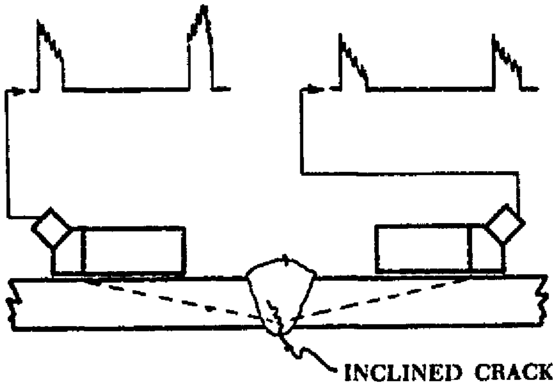


FIGURE 98. Identification of flaw types in weld zone.

One of the most difficult nondestructive tests to perform, either radiographically or ultrasonically, is the inspection of resistance-type welds. X-ray techniques are not particularly useful in this application, since in resistance welding two identical metals are fused, which results in essentially no change in density. However, with an Ultrasonic Image conversion system an evaluation of a resistance weld can be made if there is sufficient bonding between the pieces of material to obtain continuous sound transmission. The testing of resistance welds essentially resolves itself to the examination of bond to nonbond areas. If there are areas lacking bond, sufficient impedance mismatch is introduced so that attenuation of the sound energy becomes apparent. Equipment currently available is capable of detecting most discontinuities in the surface, near-surface, and deep-seated regions of a test specimen.

INSPECTION OF INTEGRAL FUEL TANKS FOR CORROSION

GENERAL:

The existence of micro-organisms in petroleum distillate products, used in turbine-powered aircraft, results in failure of integral fuel tank coatings and corrosion of the wing skins. Although corrective measures are being initiated by the petroleum industry and others to eliminate this microbiological activity in jet fuels, problems with internal corrosion pitting and surface attacks in aircraft fuel tanks continue to be experienced.

Ultrasonic nondestructive testing is used to determine the airworthiness status of jet-powered aircraft by providing a positive, accurate method of inspection for the detection and degree of corrosion in integral wing fuel tanks.

METHOD:

Standard ultrasonic inspection techniques are used for determining and recording the condition of the interior surfaces of wet-wings. Longitudinal waves should be used since shear and plate waves will not accurately establish the definition or extent of corrosion pits.

Optimum results are obtained by using a 10.0 mc focused lithium sulphate transducer of at least ½″ active element diameter. The focal length should be 3½″ to 4″ with the point of focus at the back surface of the thinnest plate.

EQUIPMENT:

To scan the underneath surface of an aircraft wing, the following equipment was developed by Sperry and is utilized by the Air Force and some airlines.

(1) A wheel search unit. To assure a satisfactory coupling, the surface to be scanned is moistened.

(2) An oscilloscope with a fast pulse repetition rate. This is necessary to conduct a rapid scan of 500 square inches or more in 15 minutes.

(3) A C-scan facsimile recorder.

(4) An automatic and manually controlled scanning bridge and carriage.

(5) A positioning mechanism, scanner support structure, and lift platform. This equipment places the wheel search unit in a position to scan the lower surface of the wing and provides the apparatus necessary to relate the motion of the search unit to the facsimile recorder. This equipment also permits a rapid engagement of the scanner with the aircraft and requires no jacking or other handling of the aircraft, nor is it necessary to drain the fuel tanks.

INDICATIONS:

Intergranular corrosion appears on the C-scan recording as a solid area projecting outward from fastener holes or other locations where there is a transverse cut exposing the edge of the plate. Large or small areas of pit-type corrosion may appear anywhere on the recording with high-density areas giving a mottled appearance to the recording. Thus, the extent and the kind of corrosion can be determined from the recording.

INSPECTION OF MISCELLANEOUS AIRCRAFT PARTS

Due to the limited nature of this digest and the large variety of parts that are being inspected with ultrasonics in the aircraft industry, only a few representative inspections that are currently being conducted are briefly discussed.

MAIN AND NOSE LANDING GEAR WHEELS:

Figure 99 illustrates the part to be examined. A surface-wave probe is used to scan around the wheel web for cracks occurring adjacent to the bosses of the tie-bolt holes. The surface wave is able to detect cracks which are not always shown up by other methods of examination. The frequency used is 2.5 mc and the depth of penetration is approximately 0.060″.

For cracks occurring in the zone of the tire areas, a second probe, having an angle of 30° refraction, is sometimes employed for testing the bead seat radius where the test is carried out without disassembly of the wheel. The angle is necessary to direct the beam away from any reflecting surfaces, such as changes in contour, into the zone where defects occur.

MAIN LANDING GEAR TORSION LINK:

A 2.5 mc surface-wave probe is applied to the member on its surface with the beam directed towards suspected zones. It is normal to scan most of the surface of the torsion link for fatigue cracks in any position occurring from the highly stressed areas (see Fig. 100).

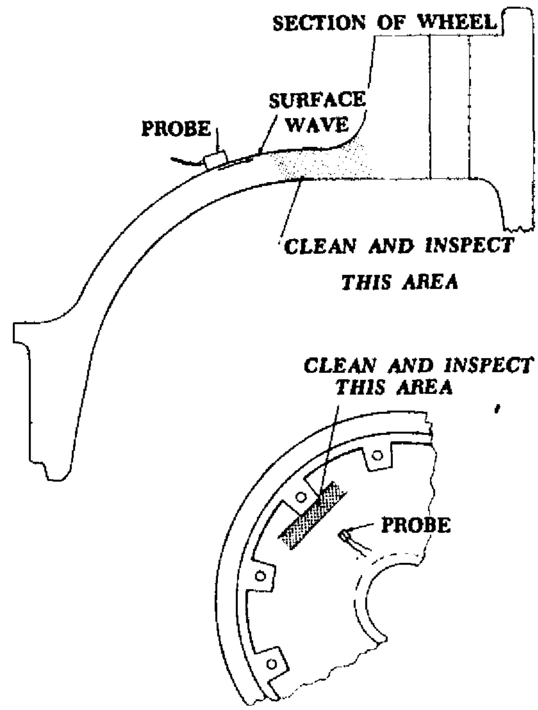


FIGURE 99. Main and nose landing gear wheels.

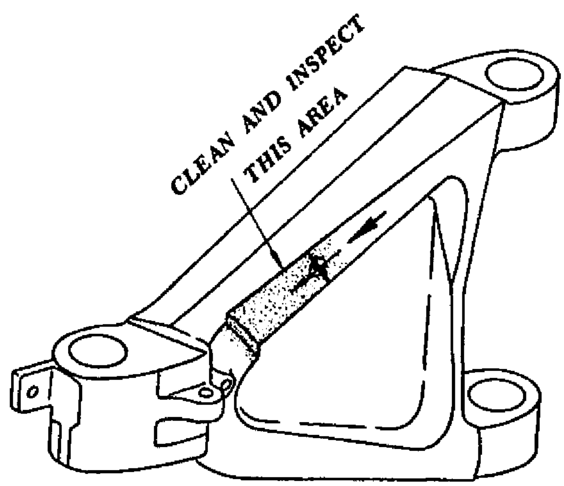


FIGURE 100. Main landing gear torsion link.

MAIN LANDING GEAR TORSION LINK LUGS:

A surface-wave probe is used on the lug surfaces and on the thickened boss section for fatigue cracks occurring in random directions. It is necessary to direct the ultrasonic sound beam towards the crack at an angle of 90° in order to obtain the optimum reflection. This means that careful scanning in all directions and in all positions around the bosses and lugs is necessary to ensure complete coverage of the suspected area (see Fig. 101).

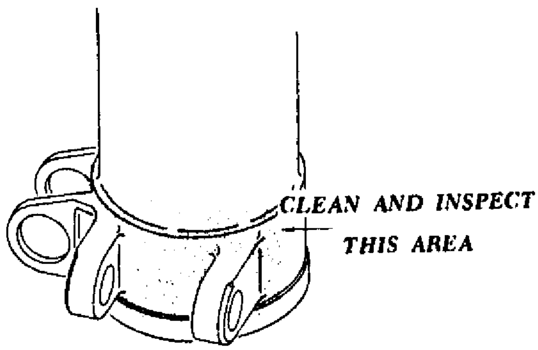


FIGURE 101. Main landing gear torsion link lugs.

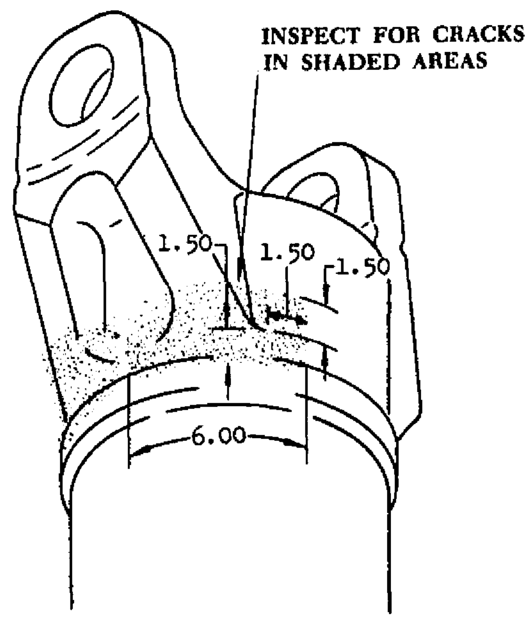


FIGURE 102. Main landing gear oleo outer cylinder.

MAIN LANDING GEAR OLEO OUTER CYLINDER:

Figure 102 indicates the zone in which high stresses produce fatigue cracks. The whole of the section concerned needs to be scanned, using a 2.5 mc surface-wave probe. Scanning is undertaken from the cylinder towards the fork ends, where the surface wave will travel around the changes in contour to locate defects in the zone indicated. Careful scanning is needed around the whole of the cylinder to find defects in any position around the base of the fork.

MAIN LANDING GEAR TRUNION SUPPORT STRUCTURE:

This examination is particularly difficult due to the geometry of the section to be inspected and due to its location on the aircraft. Very little space is available to apply the probe to the surface of the trunion support. Figure 103 indicates the areas to be inspected but does not give a true picture of the complexity of this examination.

The probe is a complex arrangement producing a beam at an angle of 30° to the surface and having locating "wings" which align the probe in the correct position by insertion of the wing between the support structure and trunion. Before undertaking this examination the area needs to be cleaned and the grease removed from around the bearings. This can be done without removing any parts from the aircraft. Because left- and right-handed parts are to be examined the probe is made in such a way that it can be located by either of two "wings" to suit the position of the part to be examined.

NOSE LANDING GEAR OUTER CYLINDER:

A 45° transverse-wave probe, 2.5 mc frequency, is used to scan the upper and lower sections of this cylinder in the areas shown in Fig. 104. The scanning is undertaken in two directions for the detection of cracks which normally occur on the inner surface but which can start on the outer surface. The two additional diagrams on the sketch show the method of scanning.

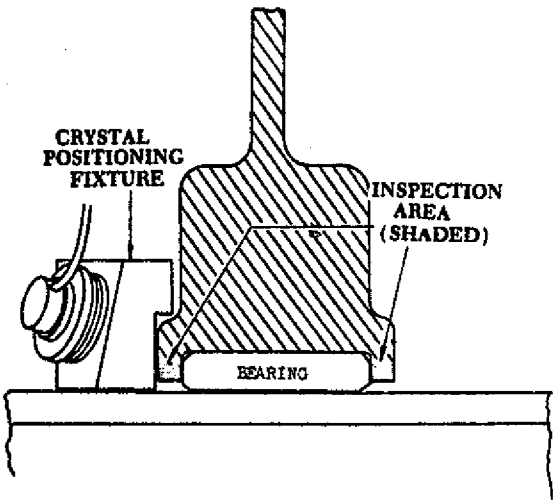


FIGURE 103. Main landing gear trunion support structure.

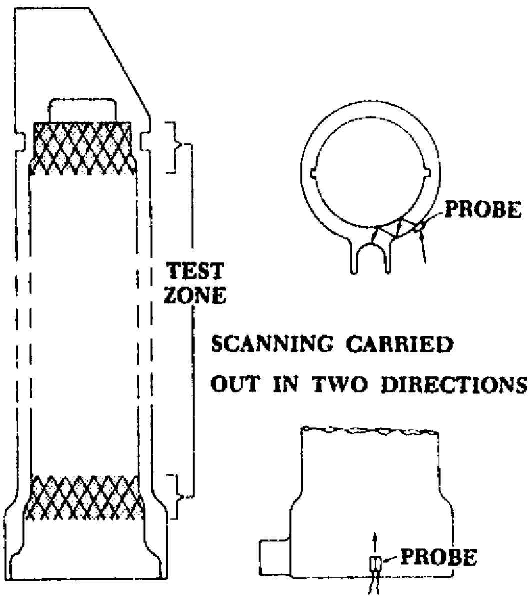


FIGURE 104. Nose landing gear outer cylinder.

INBOARD AND OUTBOARD NACELLE STRUT FRONT SPAR FITTING:

Most of the examination of these components is undertaken on the curved sections of the lugs. The angle of the beam is approximately 20° from the tangent of the circle. To obtain this angle the probe must have an incident angle of approximately 9°. Inspection is undertaken around the whole of the curved surface which gives more or less complete coverage of the bolt hole by moving a probe in two directions. In order to direct the beam towards any position of the hole in the lug, the probe has to be moved across the lug section from side to side while being rotated around the curved surface. This leaves a small section of the hole at the back of the lug which is not inspected. This is undertaken by a probe having a smaller angle and a slight taper on the lug surface. Both upper and lower parts of the lug have to be inspected by this method so that the entire bolt-hole section is examined. To facilitate examination from the curved surface, the probe surface is also curved. On some aircraft this radius differs so that two probes would normally be necessary. Practice has indicated that a probe having a larger radius can be used on lugs of the smaller radius (see Fig. 105).

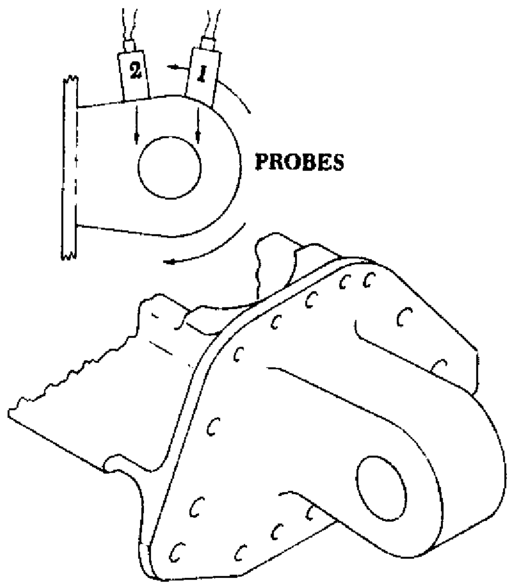


FIGURE 105. Inboard and outboard nacelle strut front spar fitting.

NOSE LANDING GEAR OUTER CYLINDER:

Figure 106 shows the area of test undertaken using a surface-wave probe with a frequency of 2.5 mc. The probe is applied to the curved surface of the cylinder and the beam directed towards the lug. The sound wave follows the surface of the material and penetrates the flat surface of the lug for the detection of defects from the corner of the sections into the lug zones marked on the sketch.

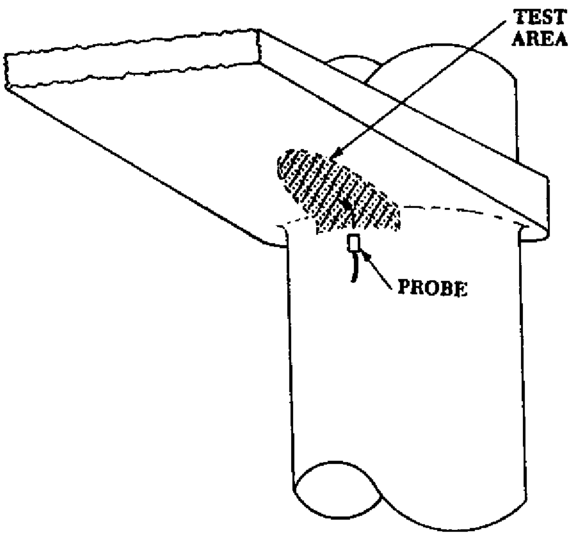


FIGURE 106. Nose landing gear outer cylinder.

CONCLUSION

The advantages of ultrasonic testing are many, and with the ever increasing demand for reliability, this valuable supercritical inspection tool helps to assure that materials from which aircraft products are fabricated perform within the limits of their design requirements. However, it must be remembered that the establishment of final in-plant levels of acceptance or rejection must depend upon correlation studies between the ultrasonic test results and other nondestructive or destruction examinations, from which meaningful test specifications and procedures can be derived.

Within sight are ultrasonic means for detecting and measuring internal stresses and prediction of fatigue failures; the instrumentation for better evaluation of defect size and shape by three-dimensional display or by multifrequency examination; the improvement of search units and techniques for high-temperature testing; better methods for more rigorous testing of cast and large-grain materials; and a means for recording the results of weld testing comparable to a radiograph.

REFERENCE DATA

ULTRASONIC SPECTRUM (IN CPS):

16-20 kc	Upper limit human hearing and division between sonic and ultrasonic. Underwater work involving magnetostrictive transducers. Drilling, soldering, and cleaning applications.
25 kc	Ultrasonic control apparatus–door opening systems, etc.
30 kc	Upper limit produced by friction.
40 kc	Common for underwater signalling and cleaning.
60 kc	Practical limit for magnetostrictive transducers.
90 kc	Upper limit for tuning forks.
100 kc	Limit for Galton whistle.
300 kc	Limit to ultrasonic generation by spark discharge.
500 kc	Lower limit for common nondestructive testing for coarse-grain structures. Upper limit to underwater signalling.
1-5 mc	Common test frequency for normal materials.
5-15 mc	Test frequencies for fine-grain materials.
1000 mc	Highest ultrasonic frequency reported attained.

ACOUSTIC VELOCITY:

1. $c = \frac{x}{t}$

Where: x = distance travelled
t = transit time

e.g. screen reading for measuring the acoustic velocity

$$c \text{ (desired velocity)} = 5900 \frac{l_1}{l_2}$$

Where: l_1 = length of test object measured mechanically
l_2 = reading on screen (when calibrating in steel c = 5900).

2. $c = f\lambda$

Where: f = frequency
λ = wavelength

e.g. c(steel) = 5900 m/s, f = 1 mc/s from which λ = 5.9 mm.

RELATIONSHIP BETWEEN ACOUSTIC VELOCITY AND ELASTIC CONSTANTS:

1. $\delta = \frac{\frac{1}{2}c(l)^2 - c(t)^2}{c(l)^2 - c(t)^2}$ = Poisson's ratio

Where:
c(l) = longitudinal acoustic velocity
c(t) = transverse acoustic velocity.

2. $\mu = 1.02 \cdot 10^{-4}\, c(t)^2 \cdot \rho$ (kgf/mm²)
μ = shear modulus, c(t) = transverse acoustic velocity,
ρ = density.

3. $E = 2\mu(1 + \zeta)$ (kgf/mm²)
E = Young's modulus.

4. $E = 4.08 \cdot 10^{-4} \cdot \rho \frac{\frac{3}{4}c(l)^2 - c(t)^2}{[c(l)^2/c(t)^2] - 1}$

REFRACTION AND REFLECTION:

1. Snell's law

$$\frac{\sin\alpha}{\sin\beta} = \frac{c(A)}{c(B)}$$

Where: α = angle of incidence,
c(A) = velocity in medium A,
β = angle of refraction,
c(B) = velocity in medium B.

2. Law of reflection

$$\alpha_1 = \alpha_2$$

Where: α_1 = angle of incidence,
α_2 = angle of reflection.

This only applies to waves of the same kind.

2a. Law of reflection when accompanied by wave conversion

$$\frac{\sin\alpha_1}{\sin\alpha_2} = \frac{c_1}{c_2}$$

all measured in medium A.

3. Condition for total internal reflection

$$\sin\alpha = c(A)/c(B)$$
$$(\sin\beta = 1,\ \beta = 90°)$$

4. Reflection factor R_I (ratio of reflected to incident intensity)

$$R_I = \frac{(m-1)^2}{(m+1)^2}$$

Where:

$$m = \frac{\rho(A) \cdot c(A)}{\rho(B) \cdot c(B)}$$

Where: $\rho(A)$ = density of A,
c(A) = velocity in A,
$\rho(B)$ = density of B,
c(B) = velocity in B.

5. Transmission factor D_I = ratio of the emergent to the incident sound intensity

$$D_I = 1 - R_I = \frac{4m}{(m+1)^2}$$

6. Reflectivity R (ratio of the reflected to the incident sound amplitude)

$$R = \frac{m-1}{m+1}$$

7. Transmissivity D_p (ratio of transmitted to incident sound pressure amplitude)

$$D_p = \frac{2m}{m+1}$$

SOUND EMISSION OF THE PROBE:

1. *Angle of divergence in far field*

   $\sin y = 1.08\ (\lambda/D) = 1.08\ (c/f).\ D$

   (decrease in amplitude to 10%)

   λ = wavelength,

   D = diameter of transducer,

   f = sound frequency,

   c = acoustic velocity.

2. Length of near field N_o

   $N_o = 0.25\ D^2/\lambda = 0.25\ D^2f/c$

ABSORPTION OF SOUND WAVES:

$$A(x) = A_o \cdot e^{-\alpha x}$$

(only applicable to plane-front waves)

A (x) = amplitude at point x,

A_o = amplitude at point x = 0,

α = coefficient of absorption in Neper,

x = distance travelled.

(1 Neper = 8.686 db) (db = decibel)

The wavelengths of ultrasonic vibrations vary not only with the frequency, but also with the physical composition of material through which they are traveling. The wavelength may be considered constant for any given material and test frequency used for each type of material under test.

ULTRASONIC PROPERTIES OF COMMON MATERIALS

	Velocity		Transmission Time		Density
Material	cm. per *microsec*	in. per *microsec*	microsec *per cm.*	microsec *per in.*	g per *cu. cm.*
Aluminum 2SO	.635	.250	1.57	4.00	2.71
Aluminum 17ST	.625	.246	1.60	4.07	2.80
Beryllium	1.28	.530	.782	1.89	1.82
Brass	.443	.175	2.26	5.72	8.1
Bronze, Phosphor	.353	.138	2.83	7.25	8.86
Copper	.466	.184	2.15	5.44	8.9
Magnesium AM35	.579	.228	1.73	4.39	1.74
Mercury	.142	.056	7.05	17.9	13.00
Molybdenum	.629	.248	1.59	4.04	10.09
Nickel	.563	.223	1.78	4.48	8.8
Nickel, Inconel	.782	.308	1.28	3.42	8.25
Nickel, Monel	.602	.236	1.66	4.24	8.83
Nickel, Silver	.462	.182	2.17	5.50	8.75
Steel	.585	.231	1.72	4.33	7.8
Steel, Stainless 302	.566	.233	1.77	4.49	8.03
Titanium 150A	.610	.240	1.64	4.17	4.54
Tungsten	.518	.204	1.93	4.90	19.25
Bakelite	.259	.102	3.89	9.81	1.4
Polystyrene	.267	.105	3.75	9.53	1.1
Pyrene	.557	.220	1.80	4.55	2.23
Air	.033	.013	30.3	77.0	.0012
Oil	.138	.054	7.25	18.5	.92
Water	.143	.056	7.00	17.9	1.0

COMMONLY USED SPECIFICATIONS AND STANDARDS

Issued by	Date	Number	Title/Explanation	Where to Obtain
ASTM	1961	E127–64	Reference Blocks, Aluminum Alloy Ultrasonic Standard, Rec. Practice for Fabricating & Checking	ASTM, 1916 Race Street Philadelphia, Pa. 19103
ASTM	1955	E114–63	Reflection Method Using Pulsed Longitudinal Waves Induced by Direct Contact	"
ASTM	1955	E113–55T	Rec. Practice for Ultrasonic Testing by Resonance Method	"
ASTM	1959	A388–59	Rec. Practice for Ultrasonic Testing & Inspection of Heavy Steel Forgings	"
ASTM	1964	A435–64	Method & Specification for Ultrasonic Testing & Inspection of Steel Plates of Firebox & Higher Quality	"
ASTM	1964	A418–64	Method for Ultrasonic Testing and Inspection of Turbine & Generator Steel Rotor Forgings	"
ASTM	1962	E164–65	Method for Ultrasonic Contact Inspection of Weldments	"
SAE		AMS–2630	Ultrasonic Inspection	Society of Automotive Engineers (SAE), 485 Lexington Ave., New York, N.Y. 10017
ASTM	1963	E213–63T Proposed Tentative	Ultrasonic Inspection of Metal Pipe & Tubing for Longitudinal Discontinuities	ASTM, Report of Committee E—7, Price $.60
ASTM	1963	E214–63T Proposed Tentative	Immersed Ultrasonic Testing by the Reflection Method Using Pulsed Longitudinal Waves	ASTM, 1916 Race Street, Philadelphia, Pa. 19103
NAS	5–15–63	NAS 824 Proposed	Inspection, Ultrasonic, Wrought Metal	Aerospace Industries Assn. 1725 De Sales St., Washington, D.C. 20036
AISI	4–59		Ultrasonic Inspection of Steel Products	AISI
ASTM	1955	A376–64	Tentative Specifications for Seamless Austenitic Steel for High-Temperature Central Station Service	ASTM, 1916 Race Street Philadelphia, Pa. 19103
SNT Airframe Committee	Feb. 1964		Recommended Ultrasonic Acceptance Standards for Airframe Aluminum Alloy Plate, Forgings & Extrusions	SNT, 914 Chicago Avenue, Evanston, Illinois, ($.25)
U.S. Gov't.	28 Aug. 64	MIL–I–8950	Inspection, Ultrasonics, Wrought Metals, Process for	U.S. Government

Issued by	Date	Number	Title/Explanation	Where to Obtain
U.S. Gov't.	26 May 64	MIL–U–81055	Ultrasonic Inspection, Immersion, of Wrought Metal, General Specification for (Torpedo MK 46 MOD O)	U.S. Government
AISI	4–59		Industry Practices for Ultrasonic Nondestructive Testing of Steel Tubular Products	American Iron & Steel Institute, New York

SYMBOLS USED IN ULTRASONIC TESTING

c/sec .... Cycles per second.

Kc/sec .... Kilocycles per second (1,000 cycles or c/sec $\times 10^3$)

Hz .... Hertz = 1 cycle/sec.

KHz .... Kilo-Hertz = (1,000 cycles/sec.)

MHz .... Mega-Hertz = (1,000,000 cycles/sec or c/sec $\times 10^6$)

c_L .... Longitudinal velocity.

c_T .... Transverse velocity.

γ .... Gamma; Beam spread angle (angle of divergence)

db .... Decibel (20 log A1/A2)

α .... Alpha; Incident angle.

α_T .... Incident angle for transverse waves.

α_L .... Incident angle for longitudinal waves.

β .... Beta; Angle of refraction.

β_T .... Angle of refraction for transverse wave.

β_L .... Angle of refraction for longitudinal waves.

α_1 .... Lower critical angle.

α_2 .... Upper critical angle.

t .... Depth or thickness.

ϵ .... Epsilon: (Complimentary angle to or angle between surface and centerline of the beam).

f .... Frequency.

λ .... Lambda; Term for wave length.

ρ .... Rho; Density.

ω .... Acoustic impedance.

R .... Reflection factor.

D_t .... Through transmission factor.

d .... Distance.

T .... Time.

μs .... Microseconds, seconds $\times 10^{-6}$.

N .... Near field.

D .... Diameter.

P .... Skip distance.

P/2 .... Half skip distance.

Z .... Dynamic amplitude.

BE .... Back Echo.

FE .... Flaw Echo.

IE .... Intermediate Echo.

VE .... Delay Echo.

a .... Surface or projected distance.

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