תדריך מעבדה – בדיקות לא הורסות

בדיקת אולטרסוניקה

מהדורה ניסויית 10/08, תעודכן על פי הערות מדריכי המעבדה והטכנאי האחראי.

נכתב על ידי יעל אבוחצירה בהנחיית פרופ' עדין שטרן.

1. תקציר:

1. הכרת השיטה האולטרסונית לזיהוי פגמים בדגם ומיקומם.
2. הכרת הציוד המשמש לביצוע הבדיקה האולטרסונית.
3. ביצוע מדידות שונות בשיטה האולטרסונית.

*נלקח מאתר האינטרנט
http://www.ndt-ed.org/EducationResources/CommunityCollege/communitycollege.htm

2. רקע תיאורטי *

2.1. Basic Principles of Ultrasonic Testing

Ultrasonic Testing (UT) uses high frequency sound energy to conduct examinations and make measurements. Ultrasonic inspection can be used for flaw detection/evaluation, dimensional measurements, material characterization, and more. To illustrate the general inspection principle, a typical pulse/echo inspection configuration as illustrated below (figure 1) will be used.
A typical UT inspection system consists of several functional units, such as the pulser/receiver, transducer, and display devices. A pulser/receiver is an electronic device that can produce high voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen. In the applet below, the reflected signal strength is displayed versus the time from signal generation to when a echo was received. Signal travel time can be directly related to the distance that the

signal traveled. From the signal, information about the reflector location, size, orientation and other features can sometimes be gained.

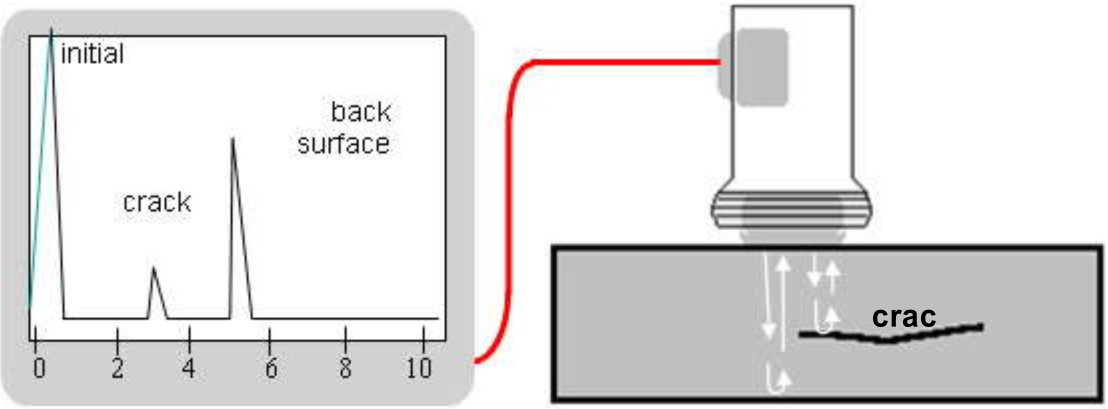


figure 1: a typical pulse/echo inspection configuration

Ultrasonic Inspection is a very useful and versatile NDT method. Some of the advantages of ultrasonic inspection that are often cited include:

- It is sensitive to both surface and subsurface discontinuities.
- The depth of penetration for flaw detection or measurement is superior to other NDT methods.
- Only single-sided access is needed when the pulse-echo technique is used.
- It is highly accurate in determining reflector position and estimating size and shape.
- Minimal part preparation is required.
- Electronic equipment provides instantaneous results.
- Detailed images can be produced with automated systems.
- It has other uses, such as thickness measurement, in addition to flaw detection.

As with all NDT methods, ultrasonic inspection also has its limitations, which include:

- Surface must be accessible to transmit ultrasound.
- Skill and training is more extensive than with some other methods.
- It normally requires a coupling medium to promote the transfer of sound energy into the test specimen.
- Materials that are rough, irregular in shape, very small, exceptionally thin or not homogeneous are difficult to inspect.

- Cast iron and other coarse grained materials are difficult to inspect due to low sound transmission and high signal noise.
- Linear defects oriented parallel to the sound beam may go undetected.
- Reference standards are required for both equipment calibration and the characterization of flaws.

2.2. Wave Propagation

Ultrasonic testing is based on time-varying deformations or vibrations in materials, which is generally referred to as acoustics. All material substances are comprised of atoms, which may be forced into vibrational motion about their equilibrium positions. Many different patterns of vibrational motion exist at the atomic level, however, most are irrelevant to acoustics and ultrasonic testing. Acoustics is focused on particles that contain many atoms that move in unison to produce a mechanical wave. When a material is not stressed in tension or compression beyond its elastic limit, its individual particles perform elastic oscillations. When the particles of a medium are displaced from their equilibrium positions, internal (electrostatic) restoration forces arise. It is these elastic restoring forces between particles, combined with inertia of the particles, that leads to the oscillatory motions of the medium.

In solids, sound waves can propagate in four principle modes that are based on the way the particles oscillate. Sound can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves. Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing. The particle movement responsible for the propagation of longitudinal and shear waves is illustrated below (figure 2).

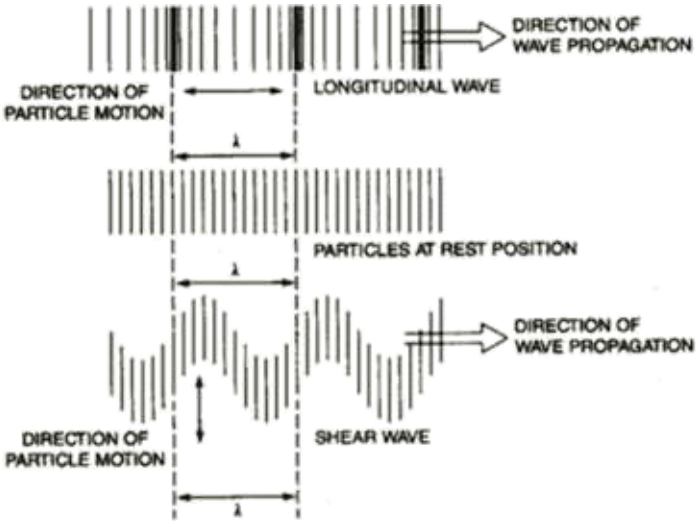


figure 2: The particle movement responsible for the propagation of longitudinal and shear waves

In longitudinal waves, the oscillations occur in the longitudinal direction or the direction of wave propagation (figure 3). Since compressional and dilational forces are active in these waves, they are also called pressure or compressional waves. They are also sometimes called density waves because their particle density fluctuates as they move. Compression waves can be generated in liquids, as well as solids because the energy travels through the atomic structure by a series of comparison and expansion (rarefaction) movements.

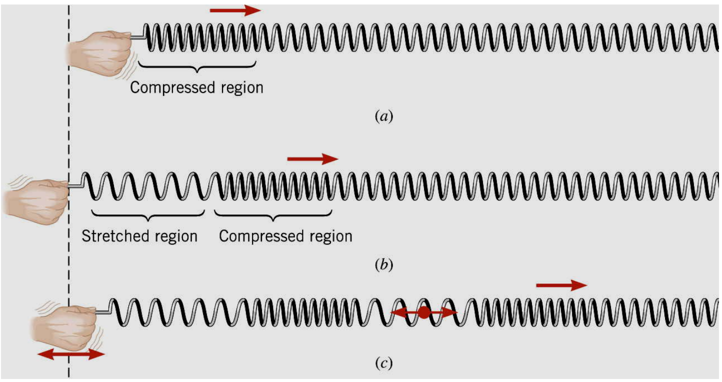


figure 3: longitudinal waves

In the transverse or shear wave, the particles oscillate at a right angle or transverse to the direction of propagation (figure 4). Shear waves require an acoustically solid material for effective propagation, and therefore, are not effectively propagated in materials such as liquids or gasses. Shear waves are relatively weak when compared to longitudinal waves. In fact, shear waves are usually generated in materials using some of the energy from longitudinal waves.

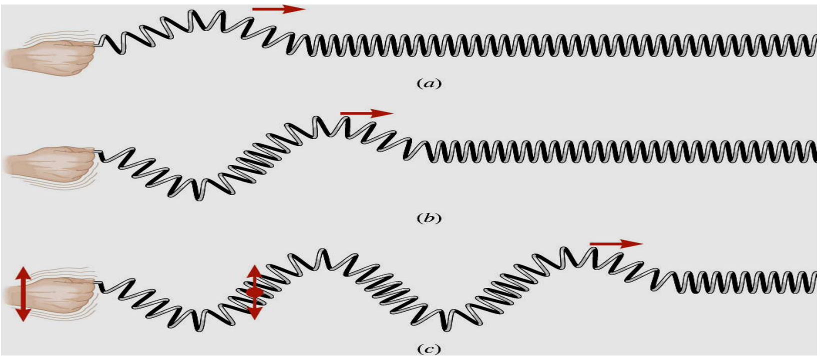


figure 4: transverse waves

2.3. Modes of Sound Wave Propagation

In air, sound travels by the compression and rarefaction of air molecules in the direction of travel. However, in solids, molecules can support vibrations in other directions, hence, a number of different types of sound waves are possible. Waves can be characterized in space by oscillatory patterns that are capable of maintaining their shape and propagating in a stable manner. The propagation of waves is often described in terms of what are called “wave modes.” As mentioned previously, longitudinal and transverse (shear) waves are most often used in ultrasonic inspection. However, at surfaces and interfaces, various types of elliptical or complex vibrations of the particles make other waves possible. Some of these wave modes such as Rayleigh and Lamb waves are also useful for ultrasonic inspection.

The table below summarizes many, but not all, of the wave modes possible in solids.

Wave Types in Solids	**Particle Vibrations**
Longitudinal	Parallel to wave direction
Transverse (Shear)	Perpendicular to wave direction
Surface - Rayleigh	Elliptical orbit - symmetrical mode
Plate Wave - Lamb	Component perpendicular to surface (extensional wave)
Plate Wave - Love	Parallel to plane layer, perpendicular to wave direction
Stoneley (Leaky Rayleigh Waves)	Wave guided along interface
Sezawa	Antisymmetric mode

Longitudinal and transverse waves were discussed on the previous page, so let's touch on surface and plate waves here.

Surface (or Rayleigh) waves travel the surface of a relatively thick solid material penetrating to a depth of one wavelength. Surface waves combine both a longitudinal and transverse motion to create an elliptic orbit motion as shown in the image below (figure 5). The major axis of the ellipse is perpendicular to the surface of the solid. As the depth of an individual atom from the surface increases the width of its elliptical motion decreases. Surface waves are generated when a longitudinal wave intersects a surface near the second critical angle and they travel at a velocity between .87 and .95 of a shear wave. Rayleigh waves are useful because they are very sensitive to surface defects (and other surface features) and they follow the surface around curves. Because of this, Rayleigh waves can be used to inspect areas that other waves might have difficulty reaching.

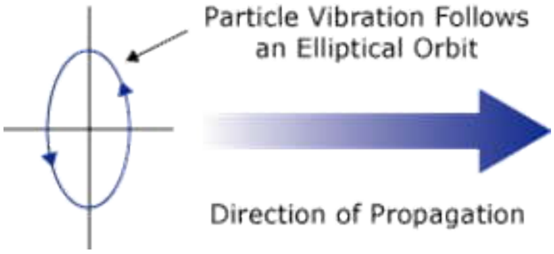


figure 5: an elliptic orbit motion of Surface waves

Plate waves are similar to surface waves except they can only be generated in materials a few wavelengths thick. Lamb waves are the most commonly used plate waves in NDT. Lamb waves are complex vibrational waves that propagate parallel to the test surface throughout the thickness of the material. Propagation of Lamb waves depends on the density and the elastic material properties of a component. They are also influenced a great deal by the test frequency and material thickness. Lamb waves are generated at an incident angle in which the parallel component of the velocity of the wave in the source is equal to the velocity of the wave in the test material. Lamb waves will travel several meters in steel and so are useful to scan plate, wire, and tubes.

With Lamb waves, a number of modes of particle vibration are possible, but the two most common are symmetrical and asymmetrical (figure 6). The complex motion of the particles is similar to the elliptical orbits for surface waves. Symmetrical Lamb waves move in a symmetrical fashion about the median plane of the plate. This is sometimes called the extensional mode because the wave is "stretching and compressing" the plate in the wave motion direction. Wave motion in the symmetrical mode is most efficiently produced when the exciting force is parallel to the plate. The asymmetrical Lamb wave mode is often called the "flexural mode" because a large portion of the motion moves in a normal direction to the plate, and a little motion occurs in the direction parallel to the plate. In this mode, the body of the plate bends as the two surfaces move in the same direction.

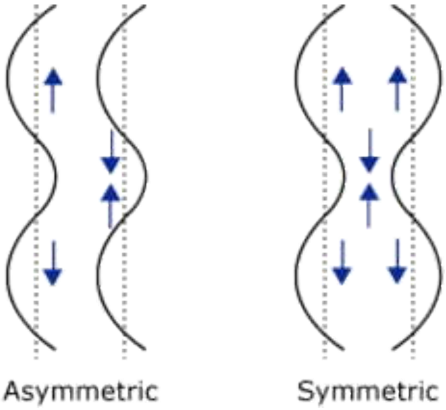


figure 6: Lamb waves, two possible modes of particle vibration

2.4. Properties of Acoustic Plane Wave

Among the properties of waves propagating in isotropic solid materials are wavelength, frequency, and velocity. The wavelength is directly proportional to the velocity of the wave and inversely proportional to the frequency of the wave. This relationship is shown by the following equation.

$$Wavelength(\lambda) = \frac{Velocity(v)}{Frequency(f)}$$

2.5. Wavelength and Defect Detection

In ultrasonic testing, the inspector must make a decision about the frequency of the transducer that will be used. Changing the frequency when the sound velocity is fixed will result in a change in the wavelength of the sound. The wavelength of the ultrasound used has a significant effect on the probability of detecting a discontinuity. A general rule of thumb is that a discontinuity must be larger than one-half the wavelength to stand a reasonable chance of being detected.

Sensitivity and resolution are two terms that are often used in ultrasonic inspection to describe a technique's ability to locate flaws. Sensitivity is the ability to locate small discontinuities. Sensitivity generally increases with higher frequency (shorter wavelengths). Resolution is the ability of the system to locate discontinuities that are close together within the material or located near the part surface. Resolution also generally increases as the frequency increases.

The wave frequency can also affect the capability of an inspection in adverse ways. Therefore, selecting the optimal inspection frequency often involves maintaining a balance between the favorable and unfavorable results of the selection. Before selecting an inspection frequency, the material's grain structure and thickness, and the discontinuity's type, size, and probable location should be considered. As frequency increases, sound tends to scatter from large or course grain structure and from small imperfections within a material. Cast materials often have coarse grains and other sound scatters that require lower frequencies to be used for evaluations of these products. Wrought and forged products with directional and refined grain structure can usually be inspected with higher frequency transducers.

Since more things in a material are likely to scatter a portion of the sound energy at higher frequencies, the penetrating power (or the maximum depth in a material that flaws can be located) is also reduced. Frequency also has an effect on the shape of the ultrasonic beam. Beam spread, or the divergence of the beam from the center axis of the transducer, and how it is affected by frequency will be discussed later.

2.6. Sound Propagation in Elastic Materials

In the previous pages, it was pointed out that sound waves propagate due to the vibrations or oscillatory motions of particles within a material. An ultrasonic wave may be visualized as an infinite number of oscillating masses or particles connected by means of elastic springs (figure 7). Each individual particle is influenced by the motion of its nearest neighbor and both inertial and elastic restoring forces act upon each particle.

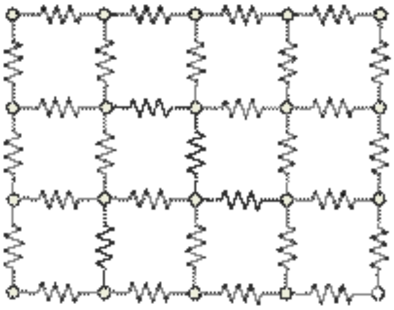


figure 7: infinite number of oscillating masses or particles connected by means of elastic springs

A mass on a spring has a single resonant frequency determined by its spring constant **k** and its mass **m**. The spring constant is the restoring force of a spring per unit of length. Within the elastic limit of any material, there is a linear relationship between the displacement of a particle and the force attempting to restore the particle to its equilibrium position. This linear dependency is described by **Hooke's Law**, In terms of the spring model, Hooke's Law says that the restoring force due to a spring is proportional to the length that the spring is stretched, and acts in the opposite direction (figure 8). Mathematically, Hooke's Law is written as **F =-kx**, where **F** is the force, **k** is the spring constant, and **x** is the amount of particle displacement.

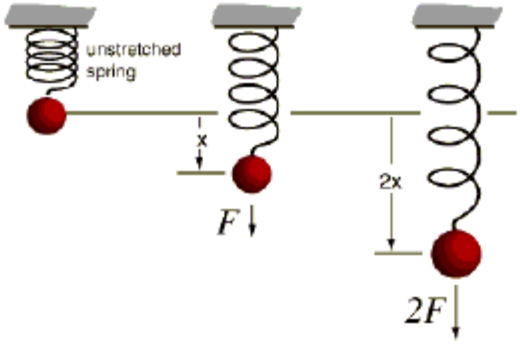


figure 8: Hooke's Law

2.7. The Speed of Sound

Hooke's Law, when used along with Newton's Second Law, can explain a few things about the speed of sound. The speed of sound within a material is a function of the properties of the material and is independent of the amplitude of the sound wave. Newton's Second Law says that the force applied to a particle will be balanced by the particle's mass and the acceleration of the particle. Mathematically, Newton's Second Law is written as **F = ma**. Hooke's Law then says that this force will be balanced by a force in the opposite direction that is dependent on the amount of displacement and the spring constant (**F = -kx**). Therefore, since the applied force and the restoring force are equal, **ma = -kx** can be written**.** The negative sign indicates that the force is in the opposite direction.

Since the mass **m** and the spring constant **k** are constants for any given material, it can be seen that the acceleration **a** and the displacement **x** are the only variables. It can also be seen that they are directly proportional. For instance, if the displacement of the particle increases, so does its acceleration. It turns out that the time that it takes a particle to move and return to its equilibrium position is independent of the force applied. So, within a given material, sound always travels at the same speed no matter how much force is applied when other variables, such as temperature, are held constant.

2.7.1. **What properties of material affect its speed of sound?**

Of course, sound does travel at different speeds in different materials. This is because the mass of the atomic particles and the spring constants are different for different materials. The mass of the particles is related to the density of the material, and the spring constant is related to the elastic constants of a material. The general relationship between the speed of sound in a solid and its density and elastic constants is given by the following equation: $V = \sqrt{\frac{C}{\rho}}$.

Where **V** is the speed of sound, **C** is the elastic constant, and ρ is the material density. This equation may take a number of different forms depending on the type of wave (longitudinal or shear) and which of the elastic constants that are used. The typical elastic constants of a materials include:

- Young's Modulus, **E**: a proportionality constant between uniaxial stress and strain.

- Poisson's Ratio, **n**: the ratio of radial strain to axial strain
- Bulk modulus, **K**: a measure of the incompressibility of a body subjected to hydrostatic pressure.
- Shear Modulus, **G**: also called rigidity, a measure of a substance's resistance to shear.
- Lame's Constants, **l** and **m**: material constants that are derived from Young's Modulus and Poisson's Ratio.

When calculating the velocity of a longitudinal wave, Young's Modulus and Poisson's Ratio are commonly used. When calculating the velocity of a shear wave, the shear modulus is used. It is often most convenient to make the calculations using Lame's Constants, which are derived from Young's Modulus and Poisson's Ratio. Examples of approximate compressional sound velocities in materials are:

- Aluminum - 0.632 cm/microsecond
- 1020 steel - 0.589 cm/microsecond
- Cast iron - 0.480 cm/microsecond.

Examples of approximate shear sound velocities in materials are:

- Aluminum - 0.313 cm/microsecond
- 1020 steel - 0.324 cm/microsecond
- Cast iron - 0.240 cm/microsecond.

When comparing compressional and shear velocities, it can be noted that shear velocity is approximately one half that of compressional velocity.

2.8. Attenuation of Sound Waves

When sound travels through a medium, its intensity diminishes with distance. In idealized materials, sound pressure (signal amplitude) is only reduced by the spreading of the wave. Natural materials, however, all produce an effect which further weakens the sound. This further weakening results from scattering and absorption. Scattering is the reflection of the sound in directions other than its original direction of propagation. Absorption is the conversion of the sound energy to other forms of energy. The combined effect of scattering and absorption is called **attenuation**.

Ultrasonic attenuation is the decay rate of the wave as it propagates through material (figure 9).

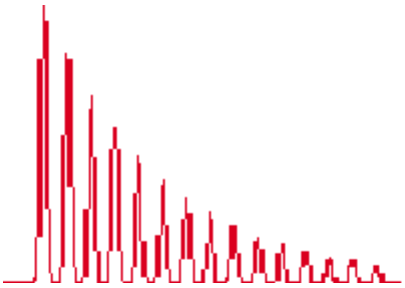


figure 9: Ultrasonic attenuation

The amplitude change of a decaying plane wave can be expressed as:

$$A = A_o e^{-\alpha Z}$$

In this expression **A_0** is the unattenuated amplitude of the propagating wave at some location. The amplitude **A** is the reduced amplitude after the wave has traveled a distance **Z** from that initial location. The quantity **α** is the attenuation coefficient of the wave traveling in the z-direction. The dimensions of **α** are nepers/length, where a neper is a dimensionless quantity. The term **e** is the exponential (or Napier's constant) which is equal to approximately 2.71828.

The units of the attenuation value in Nepers per meter (Np/m) can be converted to decibels/length by dividing by 0.1151. Decibels is a more common unit when relating the amplitudes of two signals. Attenuation is generally proportional to the square of sound frequency. Quoted values of attenuation are often given for a single frequency, or an attenuation value averaged over many frequencies may be given. Also, the actual value of the attenuation coefficient for a given material is highly dependent on the way in which the material was manufactured. Thus, quoted values of attenuation only give a rough indication of the attenuation and should not be automatically trusted. Generally, a reliable value of attenuation can only be obtained by determining the attenuation experimentally for the particular material being used. Attenuation can be determined by evaluating the multiple backwall reflections seen in a typical A-scan display like the one shown in the image at the top of the page. The number of decibels between two adjacent signals is measured and this value is divided by the time interval between them. This calculation produces a attenuation coefficient in decibels per unit time **Ut**. This value can be converted to nepers/length by the following equation.

$$\alpha = \frac{0.1151}{v} Ut$$

Where **v** is the velocity of sound in meters per second and **Ut** is in decibels per second.

2.9. Acoustic Impedance

Sound travels through materials under the influence of sound pressure. Because molecules or atoms of a solid are bound elastically to one another, the excess pressure results in a wave propagating through the solid.

The **acoustic impedance** (**Z**) of a material is defined as the product of its density (**p**) and acoustic velocity (**V**).

Z = pV

Acoustic impedance is important in

- the determination of acoustic transmission and reflection at the boundary of two materials having different acoustic impedances.
- the design of ultrasonic transducers.
- assessing absorption of sound in a medium.

2.10. Reflection and Transmission Coefficients (Pressure)

Ultrasonic waves are reflected at boundaries where there is a difference in acoustic impedances (Z) of the materials on each side of the boundary. This difference in Z is commonly referred to as the impedance mismatch. The greater the impedance mismatch, the greater the percentage of energy that will be reflected at the interface or boundary between one medium and another.

The fraction of the incident wave intensity that is refracted can be derived because particle velocity and local particle pressures must be continuous across the boundary. When the acoustic impedances of the materials on both sides of the boundary are known, the fraction of the incident wave intensity that is reflected can be calculated with the equation below. The value produced is known as the reflection coefficient. Multiplying the reflection coefficient by 100 yields the amount of energy reflected as a percentage of the original energy.

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2$$

Since the amount of reflected energy plus the transmitted energy must equal the total amount of incident energy, the transmission coefficient is calculated by simply subtracting the reflection coefficient from one.

Note that the reflection and transmission coefficients are often expressed in decibels (dB) to allow for large changes in signal strength to be more easily compared. To convert the intensity or power of the wave to dB units, take the log of the reflection or transmission coefficient and multiply this value times 10.

If reflection and transmission at interfaces is followed through the component, only a small percentage of the original energy makes it back to the transducer, even when loss by attenuation is ignored. For example, consider an immersion inspection of a steel block (figure 10). The sound energy leaves the transducer, travels through the water, encounters the front surface of the steel, encounters the back surface of the steel and reflects back through the front surface on its way back to the transducer. At the water steel interface (front surface), 12% of the energy is transmitted. At the back surface, 88% of the 12% that made it through the front surface is reflected. This is 10.6% of the intensity of the initial incident wave. As the wave exits the part back through the front surface, only 12% of 10.6 or 1.3% of the original energy is transmitted back to the transducer.

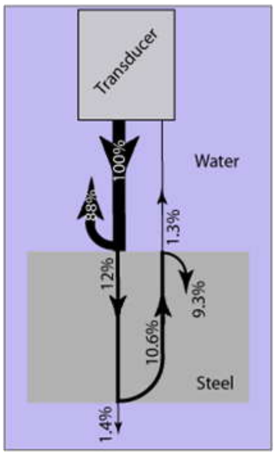


figure 10: an immersion inspection of a steel block

2.11. Refraction and Snell's Law

When an ultrasounic wave passes through an interface between two materials at an oblique angle, and the materials have different indices of refraction, both reflected and refracted waves are produced (figure 11). This also occurs with light, which is why objects seen across an interface appear to be shifted relative to where they really are. For example, if you look straight down at an object at the bottom of a glass of water, it looks closer than it really is. Refraction takes place at an interface due to the different velocities of the acoustic waves within the two materials. The velocity of sound in each material is determined by the material properties (elastic modulus and density) for that material. Snell's Law describes the relationship between the angles and the velocities of the waves. Snell's law equates the ratio of material velocities $\mathbf{V_1}$ and $\mathbf{V_2}$ to the ratio of the **sine's** of incident (θ_1) and refracted (θ_2) angles, as shown in the following equation

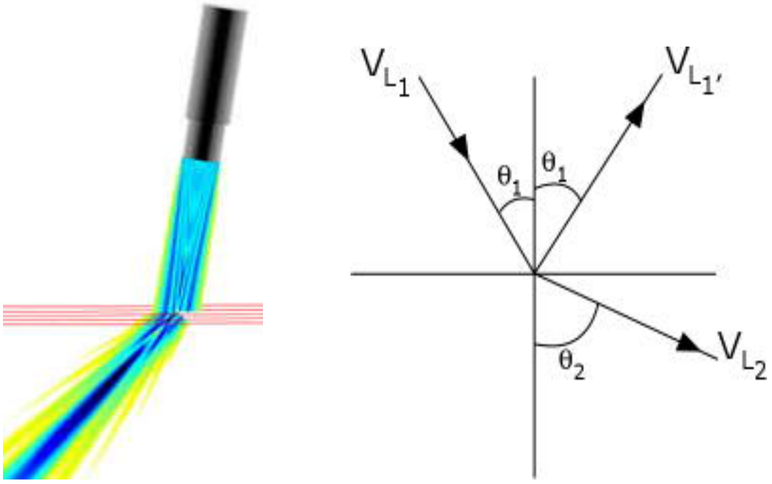


figure 11: an ultrasounic wave passes through an interface between two materials at an oblique angle

$$\frac{\sin\theta_1}{V_{L_1}} = \frac{\sin\theta_2}{V_{L2}}$$

Where:

V_{L1} is the longitudinal wave velocity in material 1.

V_{L2} is the longitudinal wave velocity in material 2.

Note that in figure 11, there is a reflected longitudinal wave (V_{L1}) shown. This wave is reflected at the same angle as the incident wave because the two waves are traveling in the same material, and hence have the same velocities. This reflected wave is unimportant in our explanation of Snell's Law, but it should be remembered that some of the wave energy is reflected at the interface. When a longitudinal wave moves from a slower to a faster material, there is an incident angle that makes the angle of refraction for the wave 90^o. This is known as the first critical angle. The first critical angle can be found from Snell's law by putting in an angle of 90° for the angle of the refracted ray. At the critical angle of incidence, much of the acoustic energy is in the form of an inhomogeneous compression wave, which travels along the interface and decays exponentially with depth from the interface. This wave is sometimes referred to as a "creep wave." Because of their inhomogeneous nature and the fact that they decay rapidly, creep waves are not used as extensively as Rayleigh surface waves in NDT. However, creep waves are sometimes more useful than Rayleigh waves because they suffer less from surface irregularities and coarse material microstructure due to their longer wavelengths.

2.12. Mode Conversion

When sound travels in a solid material, one form of wave energy can be transformed into another form. For example, when a longitudinal waves hits an interface at an angle (figure 12), some of the energy can cause particle movement in the transverse direction to start a shear (transverse) wave. Mode conversion occurs when a wave encounters an interface between materials of different acoustic impedances and the incident angle is not normal to the interface.

Snell's Law holds true for shear waves as well as longitudinal waves and can be written as follows.

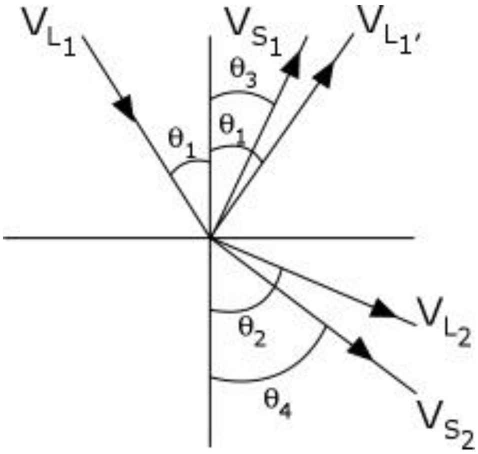


figure 12: a longitudinal waves hits an interface at an angle,

$$\frac{\sin\theta_1}{V_{L_1}} = \frac{\sin\theta_2}{V_{L2}} = \frac{\sin\theta_3}{V_{S3}} = \frac{\sin\theta_4}{V_{S4}}$$

Where:

V_{L1} is the longitudinal wave velocity in material 1.
V_{L2} is the longitudinal wave velocity in material 2.
V_{S1} is the shear wave velocity in material 1.
V_{S2} is the shear wave velocity in material 2.

when a wave moves from a slower to a faster material, there is an incident angle which makes the angle of refraction for the longitudinal wave 90 degrees. As mentioned on the previous page, this is known as the first critical angle and all of the energy from the refracted longitudinal wave is now converted to a surface following longitudinal wave. This surface following wave is sometime referred to as a creep wave and it is not very useful in NDT because it dampens out very rapidly. Beyond the first critical angle, only the shear wave propagates into the material. For this reason, most angle beam transducers use a shear wave so that the signal is not complicated by having two waves present. In may cases there is also an incident angle that makes the angle of refraction for the shear wave 90 degrees. This is know as the second critical angle and at this point, all of the wave energy is reflected or refracted into a surface following shear wave or shear creep wave. Slightly beyond the second critical angle, surface waves will be generated.

2.13. Piezoelectric Transducers

The conversion of electrical pulses to mechanical vibrations and the conversion of returned mechanical vibrations back into electrical energy is the basis for ultrasonic testing. The active element is the heart of the transducer as it converts the electrical energy to acoustic energy, and vice versa. The active element is basically a piece of polarized material (i.e. some parts of the molecule are positively charged, while other parts of the molecule are negatively charged) with electrodes attached to two of its opposite faces. When an electric field is applied across the material, the polarized molecules will align themselves with the electric field, resulting in induced dipoles within the molecular or crystal structure of the material. This alignment of molecules will cause the material to change dimensions (figure 13). This phenomenon is known as electrostriction. In addition, a permanently-polarized material such as quartz (SiO2) or barium titanate (BaTiO3) will produce an electric field when the material changes dimensions as a result of an imposed mechanical force. This phenomenon is known as the piezoelectric effect.

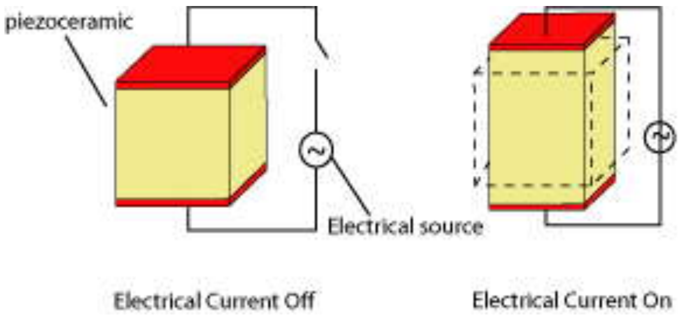


figure 13: The active element -the heart of the transducer: converts electrical energy to acoustic energy, and vice versa

The active element of most acoustic transducers used today is a piezoelectric ceramic, which can be cut in various ways to produce different wave modes, operate at low voltage and usable up to about 300°C. The thickness of the active element is determined by the desired frequency of the transducer. A thin wafer element vibrates with a wavelength that is twice its thickness. Therefore, piezoelectric crystals are cut to a thickness that is 1/2 the desired radiated wavelength. The higher the frequency of the transducer, the thinner the active element. The primary reason that high frequency contact transducers are not produced is because the element is very thin and too fragile.

2.14. Characteristics of Piezoelectric Transducers

The transducer is a very important part of the ultrasonic instrumentation system. The transducer incorporates a piezoelectric element, which converts electrical signals into mechanical vibrations (transmit mode) and mechanical vibrations into electrical signals (receive mode).

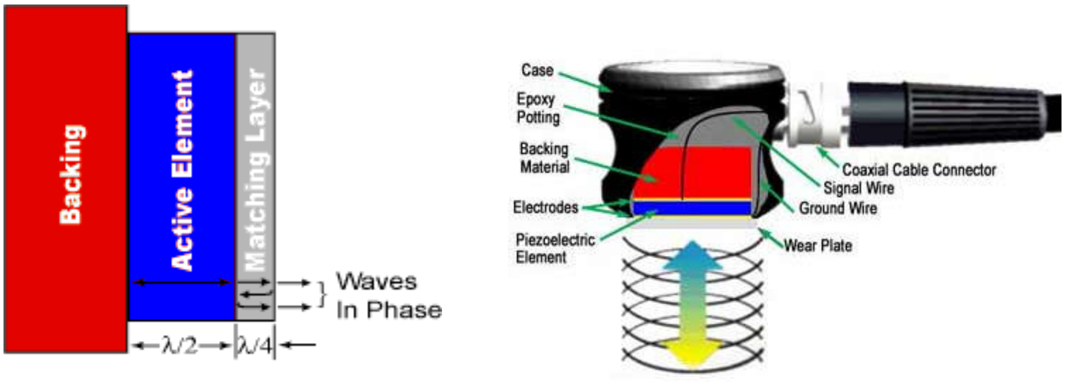


figure 14: A cut away of a typical contact transducer

Many factors, including material, mechanical and electrical construction, and the external mechanical and electrical load conditions, influence the behavior of a transducer. Mechanical construction includes parameters such as the radiation surface area, mechanical damping, housing, connector type and other variables of physical construction. A cut away of a typical contact transducer is shown above (figure 14). It was previously learned that the piezoelectric element is cut to 1/2 the desired wavelength. To get as much energy out of the transducer as possible, an impedance matching is placed between the active element and the face of the transducer. Optimal impedance matching is achieved by sizing the matching layer so that its thickness is 1/4 of the desired wavelength. This keeps waves that were reflected within the matching layer in phase when they exit the layer. For contact transducers, the matching layer is made from a material that has an acoustical impedance between the active element and steel. Immersion transducers have a matching layer with an acoustical impedance between the active element and water. Contact transducers also incorporate a wear plate to protect the matching layer and active element from scratching. The backing material supporting the crystal has a great influence on the damping characteristics of a transducer. Using a backing material with an impedance similar to that of the active element will produce the most effective damping. Such a transducer will have a wider bandwidth resulting in higher sensitivity. As the mismatch in impedance between the active element and the backing material increases, material penetration increases but transducer sensitivity is reduced

2.14.1. **Transducer Efficiency, Bandwidth and Frequency**

Some transducers are specially fabricated to be more efficient transmitters and others to be more efficient receivers. A transducer that performs well in one application will not always produce the desired results in a different application. For example, sensitivity to small defects is proportional to the product of the efficiency of the transducer as a transmitter and a receiver. Resolution, the ability to locate defects near the surface or in close proximity in the material, requires a highly damped transducer. It is also important to understand the concept of bandwidth, or range of frequencies, associated with a transducer. The frequency noted on a transducer is the central or center frequency and depends primarily on the backing material. Highly damped transducers will respond to frequencies above and below the central frequency. The broad frequency range provides a transducer with high resolving power. Less damped transducers will exhibit a narrower frequency range and poorer resolving power, but greater penetration. The central frequency will also define the capabilities of a transducer. Lower frequencies (0.5MHz-2.25MHz) provide greater energy and penetration in a material, while high frequency crystals (15.0MHz-25.0MHz) provide reduced penetration but greater sensitivity to small discontinuities. High frequency transducers, when used with the proper instrumentation, can improve flaw resolution and thickness measurement capabilities dramatically. Broadband transducers with frequencies up to 150 MHz are commercially available. Transducers are constructed to withstand some abuse, but they should be handled carefully. Misuse, such as dropping, can cause cracking of the wear plate, element, or the backing material. Damage to a transducer is often noted on the A-scan presentation as an enlargement of the initial pulse.

2.15. Radiated Fields of Ultrasonic Transducers

The sound that emanates from a piezoelectric transducer does not originate from a point, but instead originates from most of the surface of the piezoelectric element. Round transducers are often referred to as piston source transducers because the sound field resembles a cylindrical mass in front of the transducer. The sound field from a typical piezoelectric transducer is shown below (figure 15). The intensity of the sound is indicated by color, with lighter colors indicating higher intensity.

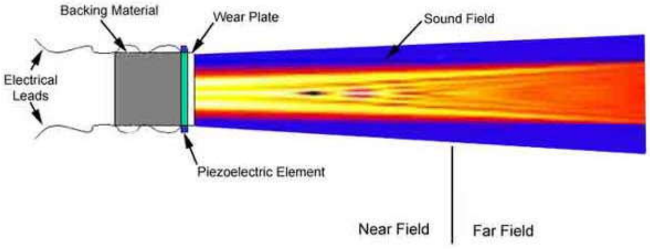


figure 15: The sound field from a typical piezoelectric transducer

Since the ultrasound originates from a number of points along the transducer face, the ultrasound intensity along the beam is affected by constructive and destructive wave interference. These are sometimes also referred to as diffraction effects. This wave interference leads to extensive fluctuations in the sound intensity near the source and is known as the near field. Because of acoustic variations within a near field, it can be extremely difficult to accurately evaluate flaws in materials when they are positioned within this area. The pressure waves combine to form a relatively uniform front at the end of the near field. The area beyond the near field where the ultrasonic beam is more uniform is called the far field. In the far field, the beam spreads out in a pattern originating from the center of the transducer. The transition between the near field and the far field occurs at a distance, ***N***, and is sometimes referred to as the "natural focus" of a flat (or unfocused) transducer. The near/far field distance, ***N***, is significant because amplitude variations that characterize the near field change to a smoothly declining amplitude at this point. The area just beyond the near field is where the sound wave is well behaved and at its maximum strength. Therefore, optimal detection results will be obtained when flaws occur in this area (figure 16).

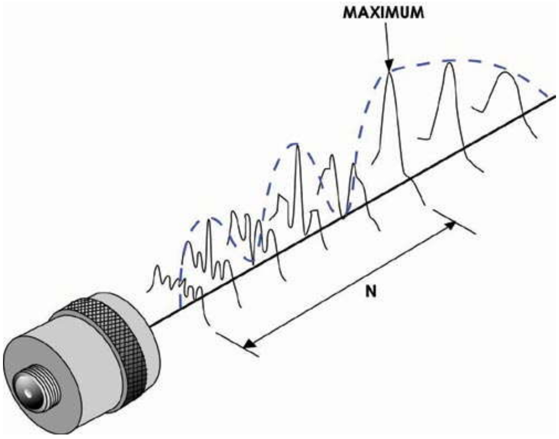


figure 16: the ultrasound intensity along the beam

2.16. Transducer Beam Spread

As discussed on the previous page, round transducers are often referred to as piston source transducers because the sound field resembles a cylindrical mass in front of the transducer (figure 17). However, the energy in the beam does not remain in a cylinder, but instead spreads out as it propagates through the material. The phenomenon is usually referred to as beam spread but is sometimes also referred to as beam divergence or ultrasonic diffraction. It should be noted that there is actually a difference between beam spread and beam divergence. Beam spread is a measure of the whole angle from side to side of the main lobe of the sound beam in the far field. Beam divergence is a measure of the angle from one side of the sound beam to the central axis of the beam in the far field. Therefore, beam spread is twice the beam divergence.

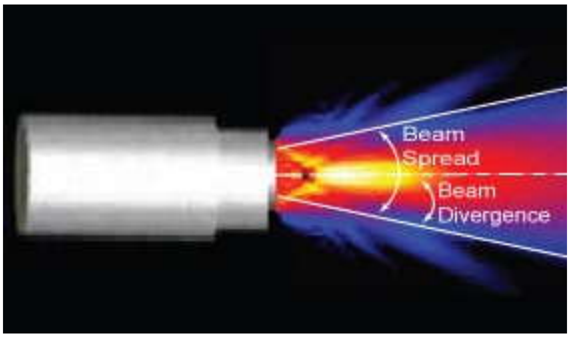


figure 17: the sound field in round transducers

Although beam spread must be considered when performing an ultrasonic inspection, it is important to note that in the far field, or Fraunhofer zone, the maximum sound pressure is always found along the acoustic axis (centerline) of the transducer. Therefore, the strongest reflections are likely to come from the area directly in front of the transducer.

Beam spread occurs because the vibrating particle of the material (through which the wave is traveling) do not always transfer all of their energy in the direction of wave propagation. Recall that waves propagate through the transfer of energy from one particle to another in the medium. If the particles are not directly aligned in the direction of wave propagation, some of the energy will get transferred off at an angle. (Picture what happens when one ball hits another ball slightly off center). In the near field, constructive and destructive wave interference fill the sound field with fluctuation. At the start of the far field, however, the beam strength is always greatest at the center of the beam and diminishes as it spreads outward.

Beam angle is an important consideration in transducer selection for a couple of reasons. First, beam spread lowers the amplitude of reflections since sound fields are less concentrated and, thereby weaker. Second, beam spread may result in more difficulty in interpreting signals due to reflections from the lateral sides of the test object or other features outside of the inspection area. Characterization of the sound field generated by a transducer is a prerequisite to understanding observed signals

2.17. Transducer Types

Ultrasonic transducers are manufactured for a variety of applications and can be custom fabricated when necessary. Careful attention must be paid to selecting the proper transducer for the application. It is important to choose transducers that have the desired frequency, bandwidth, and focusing to optimize inspection capability. Most often the transducer is chosen either to enhance the sensitivity or resolution of the system.

Transducers are classified into groups according to the application. **Contact transducers** (figure 18) are used for direct contact inspections, and are generally hand manipulated. They have elements protected in a rugged casing to withstand sliding contact with a variety of materials. These transducers have an ergonomic design so that they are easy to grip and move along a surface. They often have replaceable wear plates to lengthen their useful life. Coupling materials of water, grease, oils, or commercial materials are used to remove the air gap between the transducer and the component being inspected.

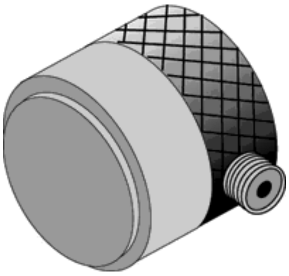


figure 18: Contact transducers

Immersion transducers (figure 19) do not contact the component. These transducers are designed to operate in a liquid environment and all connections are watertight. Immersion transducers usually have an impedance matching layer that helps to get more sound energy into the water and, in turn, into the component being inspected. Immersion transducers can be purchased with a planer, cylindrically focused or spherically focused lens. A focused transducer can improve the sensitivity and axial resolution by concentrating the sound energy to a smaller area. Immersion transducers are typically used inside a water tank or as part of a squirter or bubbler system in scanning applications.

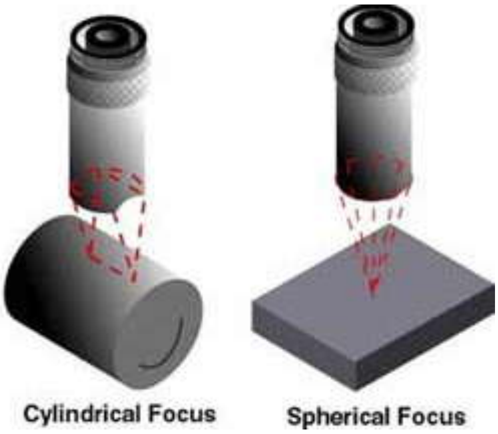


figure 19: Immersion transducers

More on Contact Transducers: Contact transducers are available in a variety of configurations to improve their usefulness for a variety of applications. The flat contact transducer shown above is used in normal beam inspections of relatively flat surfaces, and where near surface resolution is not critical. If the surface is curved, a shoe that matches the curvature of the part may need to be added to the face of the transducer. If near surface resolution is important or if an angle beam inspection is needed, one of the special contact transducers described below might be used.

Dual element transducers (figure 20) contain two independently operated elements in a single housing. One of the elements transmits and the other receives the ultrasonic signal. Active elements can be chosen for their sending and receiving capabilities to provide a transducer with a cleaner signal, and transducers for special applications, such as the inspection of course grained material. Dual element transducers are especially well suited for making measurements in applications where reflectors are very near the transducer since this design eliminates the ring down effect that single-element transducers experience when single-element transducers are operating in pulse echo mode, the element cannot start receiving reflected signals until the element has stopped ringing from its transmit function). Dual element transducers are very useful when making thickness measurements of thin materials and when inspecting for near surface defects. The two elements are angled towards each other to create a crossed-beam sound path in the test material.

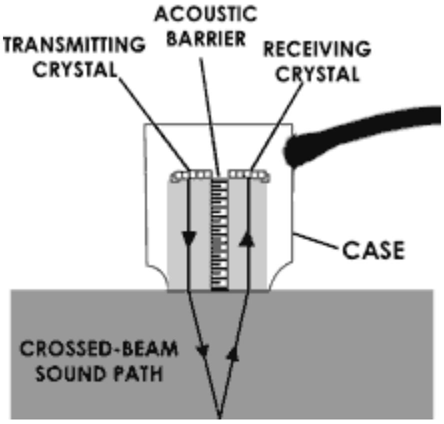


figure 20: Dual element transducers

Delay line transducers (figure 21) provide versatility with a variety of replaceable options. Removable delay line, surface conforming membrane, and protective wear cap options can make a single transducer effective for a wide range of applications. As the name implies, the primary function of a delay line transducer is to introduce a time delay between the generation of the sound wave and the arrival of any reflected waves. This allows the transducer to complete its "sending" function before it starts its "listening" function so that near surface resolution is improved. They are designed for use in applications such as high precision thickness gauging of thin materials and delamination checks in composite materials. They are also useful in high-temperature measurement applications since the delay line provides some insulation to the piezoelectric element from the heat.

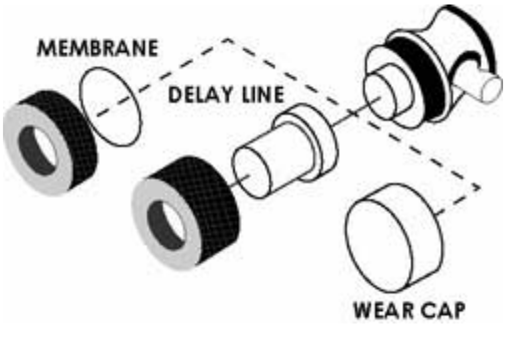


figure 21: Delay line transducers

Angle beam transducers (figure 22) and wedges are typically used to introduce a refracted shear wave into the test material. Transducers can be purchased in a variety of fixed angles or in adjustable versions where the user determines the angles of incidence and refraction. In the fixed angle versions, the angle of refraction that is marked on the transducer is only accurate for a particular material, which is usually steel. The angled sound path allows the sound beam to be reflected from the backwall to improve detectability of flaws in and around welded areas. They are also used to generate surface waves for use in detecting defects on the surface of a component.

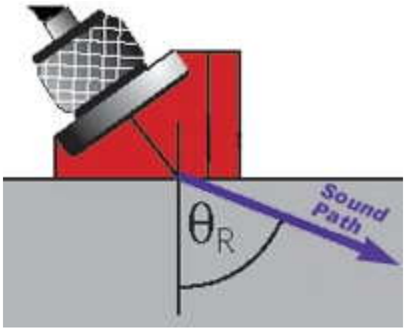


figure 22: Angle beam transducers

Normal incidence shear wave transducers are unique because they allow the introduction of shear waves directly into a test piece without the use of an angle beam wedge. Careful design has enabled manufacturing of transducers with minimal longitudinal wave contamination. The ratio of the longitudinal to shear wave components is generally below -30dB.

Paint brush transducers are used to scan wide areas. These long and narrow transducers are made up of an array of small crystals that are carefully matched to minimize variations in performance and maintain uniform sensitivity over the entire area of the transducer. Paint brush transducers make it possible to scan a larger area more rapidly for discontinuities. Smaller and more sensitive transducers are often then required to further define the details of a discontinuity.

2.18. Couplant

A couplant is a material (usually liquid) that facilitates the transmission of ultrasonic energy from the transducer into the test specimen (figure 23). Couplant is generally necessary because the acoustic impedance mismatch between air and solids (i.e. such as the test specimen) is large. Therefore, nearly all of the energy is reflected and very little is transmitted into the test material. The couplant displaces the air and makes it possible to get more sound energy into the test specimen so that a usable ultrasonic signal can be obtained. In contact ultrasonic testing a thin film of oil, glycerin or water is generally used between the transducer and the test surface.

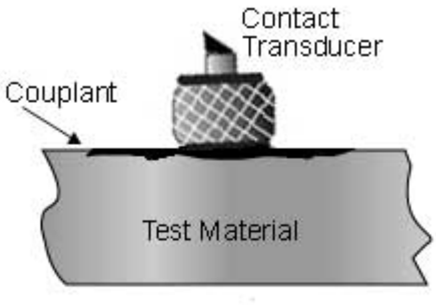


figure 23: A couplant In contact ultrasonic testing

2.19. Data Presentation

Ultrasonic data can be collected and displayed in a number of different formats. The three most common formats are know in the NDT world as **A-scan**, **B-scan** and **C-scan** presentations. Each presentation mode provides a different way of looking at and evaluating the region of material being inspected. Modern computerized ultrasonic scanning systems can display data in all three presentation forms simultaneously.

2.19.1. A-Scan Presentation

The A-scan presentation displays the amount of received ultrasonic energy as a function of time. The relative amount of received energy is plotted along the vertical axis and the elapsed time (which may be related to the sound energy travel time within the material) is displayed along the horizontal axis. Most instruments with an A-scan display allow the signal to be displayed in its natural radio frequency form (RF), as a fully rectified RF signal, or as either the positive or negative half of the RF signal. In the A-scan presentation, relative discontinuity size can be estimated by comparing the signal amplitude obtained from an unknown reflector to that from a known reflector. Reflector depth can be determined by the position of the signal on the horizontal sweep.

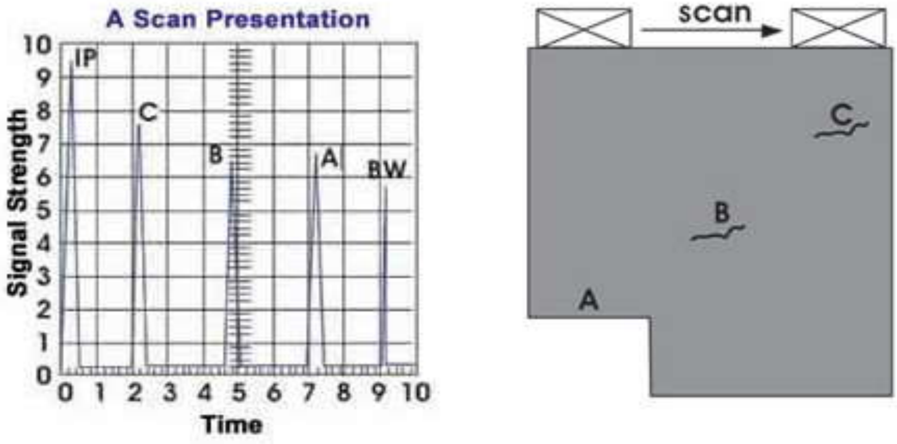


figure 24: The A-scan presentation

In the illustration of the A-scan presentation (figure 24), the initial pulse generated by the transducer is represented by the signal ***IP,*** which is near time zero. As the transducer is scanned along the surface of the part, four other signals are likely to appear at different times on the screen. When the transducer is in its far left position, only the ***IP*** signal and signal ***A***, the sound energy reflecting from surface ***A,*** will be seen on the trace. As the transducer is scanned to the right, a signal from the backwall ***BW*** will appear later in time, showing that the sound has traveled farther to reach this surface. When the transducer is over flaw ***B***, signal ***B*** will appear at a point on the time scale that is approximately halfway between the ***IP*** signal and the ***BW*** signal. Since the ***IP*** signal corresponds to the front surface of the material, this indicates that flaw ***B*** is about halfway between the front and back surfaces of the sample. When the transducer is moved over flaw ***C,*** signal ***C*** will appear earlier in time since the sound travel path is shorter and signal ***B*** will disappear since sound will no longer be reflecting from it.

2.19.2. **B-Scan Presentation**

The B-scan presentations is a profile (cross-sectional) view of the test specimen. In the B-scan, the time-of-flight (travel time) of the sound energy is displayed along the vertical axis and the linear position of the transducer is displayed along the horizontal axis (figure 25). From the B-scan, the depth of the reflector and its approximate linear dimensions in the scan direction can be determined. The B-scan is typically produced by establishing a trigger gate on the A-scan. Whenever the signal intensity is great enough to trigger the gate, a point is produced on the B-scan. The gate is triggered by the sound reflecting from the backwall of the specimen and by smaller reflectors within the material. In the B-scan image above, line ***A*** is produced as the transducer is scanned over the reduced thickness portion of the specimen. When the transducer moves to the right of this section, the backwall line ***BW*** is produced. When the transducer is over flaws ***B*** and ***C***, lines that are similar to the length of the flaws and at similar depths within the material are drawn on the B-scan. It should be noted that a limitation to this display technique is that reflectors may be masked by larger reflectors near the surface.

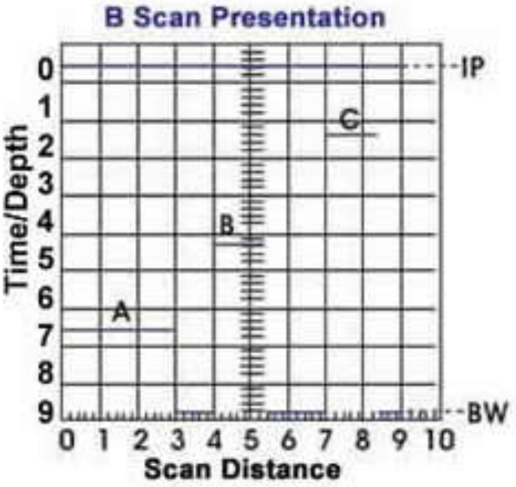


figure 25: The B-scan presentations

2.19.3. **C-Scan Presentation**

The C-scan presentation provides a plan-type view of the location and size of test specimen features. The plane of the image is parallel to the scan pattern of the transducer. C-scan presentations are produced with an automated data acquisition system, such as a computer controlled immersion scanning system. Typically, a data collection gate is established on the A-scan and the amplitude or the time-of-flight of the signal is recorded at regular intervals as the transducer is scanned over the test piece. The relative signal amplitude or the time-of-flight is displayed as a shade of gray or a color for each of the positions where data was recorded. The C-scan presentation provides an image of the features that reflect and scatter the sound within and on the surfaces of the test piece (figure 26).

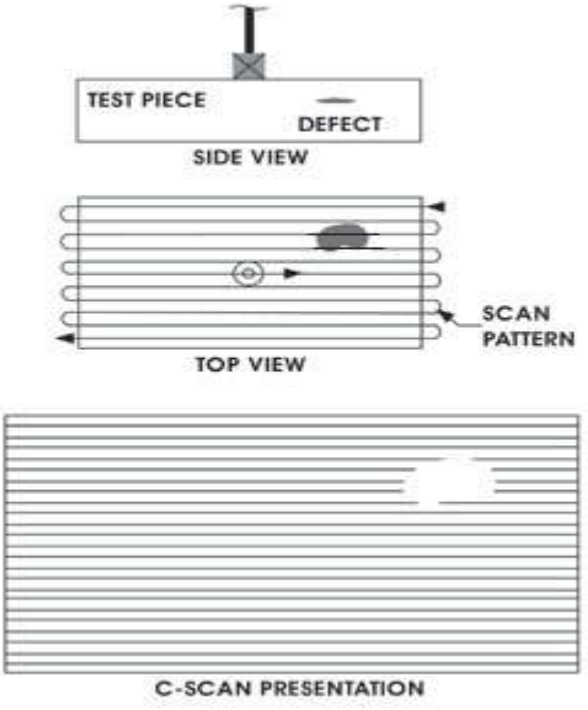


figure 26: The C-scan presentation

High resolution scans can produce very detailed images. Below are two ultrasonic C-scan images of a US quarter (figure 27). Both images were produced using a pulse-echo technique with the transducer scanned over the head side in an immersion scanning system. For the C-scan image on the left, the gate was setup to capture the amplitude of the sound reflecting from the front surface of the quarter. Light areas in the image indicate areas that reflected a greater amount of energy back to the transducer. In the C-scan image on the right, the gate was moved to record the intensity of the sound reflecting from the back surface of the coin. The details on the back surface are clearly visible but front surface features are also still visible since the sound energy is affected by these features as it travels through the front surface of the coin.

figure 27: ultrasonic C-scan images of a US quarter

2.20. Normal Beam Inspection

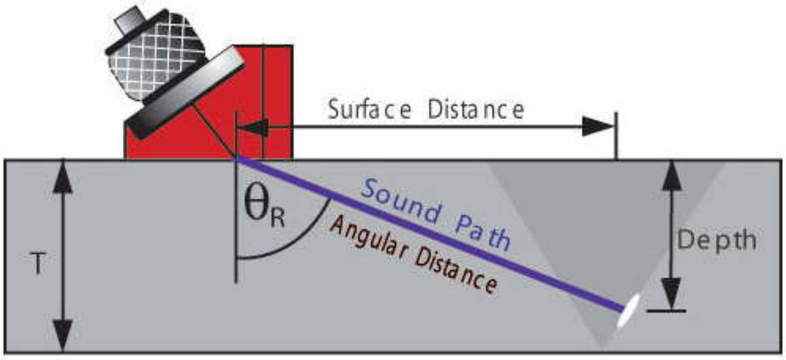
Pulse-echo ultrasonic measurements can determine the location of a discontinuity in a part or structure by accurately measuring the time required for a short ultrasonic pulse generated by a transducer to travel through a thickness of material, reflect from the back or the surface of a discontinuity, and be returned to the transducer. In most applications, this time interval is a few microseconds or less. The two-way transit time measured is divided by two to account for the down-and-back travel path and multiplied by the velocity of sound in the test material. The result is expressed in the well-known relationship

$$d = vt/2 \text{ or } v = 2d/t$$

where **d** is the distance from the surface to the discontinuity in the test piece, **v** is the velocity of sound waves in the material, and **t** is the measured round-trip transit time.

2.21. Angle Beams I

Angle Beam Transducers and wedges are typically used to introduce a refracted shear wave into the test material. An angled sound path allows the sound beam to come in from the side, thereby improving detectability of flaws in and around welded areas (figure 28).



θ_R = Angle of Refraction
T = Material Thickness
Surface Distance = $\sin\theta_R \times$ Sound Path
Depth (1st Leg) = $\cos\theta_R \times$ Sound Path

figure 28: Angle Beam I

2.22. Angle Beams II

Angle Beam Transducers and wedges are typically used to introduce a refracted shear wave into the test material. The geometry of the sample below allows the sound beam to be reflected from the back wall to improve detectability of flaws in and around welded areas (figure 29).

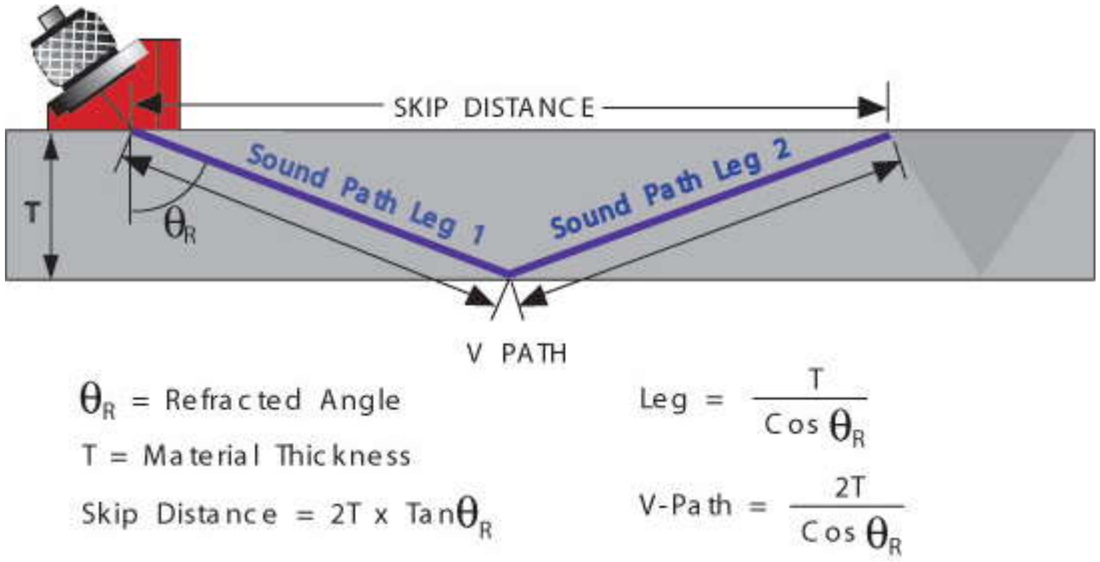


figure 29: Angle Beam II

3. מכשור:

- מכשיר אולטרסוני.
- מתמרים אורכיים : MB4S ,MB4F, K2G, BA6-5, SEB4, D-706,
- מתמרים זוויתיים : WB45-2 , WB70-2

4. מהלך הניסוי:

תוכנית הניסוי:

מס' משימה	שם המשימה	חומר/ חלק	מתמר	תוכנה במכשיר
1	הדגמה .trans method	פלדה	MB4F + MB4S	13
2	הכרת המכשיר	פלדה 40 שעות	K2G	1
3	השפעת גובה וזווית	פלדות שונות	K2G	10
4	השפעה חספוס חיצוני	3 דגמי נחושת	MB4S	18
5	מדידת CL ו- CT	זכוכית	MB4S	6
'5	מדידת CL ו- CT	סיליקון	K2G	4
"5	מדידת CL ו- CT	מגנזיום Mg	K2G	2
6	מדידת CL במתכות	אלומיניום, נחושת ופלדה	K2G	3
7	השפעת גודל גרעין	פליז : G1-4 + G2-3 +	MB2F MB4F	15 14 16

		G3-5	BA6-5	
8	פורוזיביות	אלומיניום יצוק	K2G	3
9	השפעת ה-pipe	אלומיניום יצוק	K2G	3
10	פגם לחישוב	2 דגמי חומר לא ידוע	K2G	1-3
11	lamination	אבץ	K2G	17
12	בדיקת עומק קדחים	פלדה	SEB4	5
'12	בדיקת גובה מדרגות	אלומיניום	D-706	9
13	גליל עם מתאם	פלדה ופרספקס	SEB4	12
14	זווית 45°	פלדה	WB45-2	7
15	זווית 70°	אלומיניום	WB70-2	8
16	גלי Rayleigh	פלדה	WB45-2+20°	19

**הערה: עבור בדיקות 2, 10, 15 ו-16 יש דפי עזר בנספחים.

משימה מס' 1: בדוק חלק עשוי פלדה באמצעות שני מתמרים: MB4F ו-MB4S בשיטת transmission method.

משימה מס' 2: הכרת המכשיר.
קבל מהמדריך חלק עשוי פלדה. מדוד מימדי החלק באמצעות סרגל/קליבר. בדוק את החלק באמצעות מתמר K2G. פרט מהם המשתנים הקיימים בבדיקה וכיצד ניתן לשלוט בהם.

משימה מספר 3: בחינת השפעת מימדי הדגם על הסיגנל המתקבל.
קבל מהמדריך שלושה דגמי פלדה. מדוד את מימדיהם באמצעות סרגל/קליבר. בדוק את הדגמים באמצעות גשש K2G. חשב קבוע החומר עבור פלדה.

משימה מספר 4: בחינת השפעת חספוס פני השטח החיצוניים של הדגם על הסיגנל המתקבל.
קבל מהמדריך שלושה דגמי נחושת גליליים להם דרגה שונה של חספוס פני השטח:
דגם 1: פני שטח חלקים, דגם 2: פני שטח מחוספסים, דגם 3: פני שטח מחוספסים מאוד. מדוד את מימדיהם באמצעות סרגל/קליבר.בדוק את הדגמים באמצעות גשש MB4S. קבע קבוע החומר של נחושת. מהי ההשפעה של משיכות החומר על ערכו של קבוע החומר?

משימה מס' 5: חישוב קבוע חומר של זכוכית.
קבל מהמדריך דגם זכוכית גלילי. מדוד מימדי הדגם באמצעות סרגל/קליבר. בדוק את הדגם באמצעות גששMB4S . חשב קבוע החומר עבור זכוכית. מהי ההשפעה של משיכות החומר על

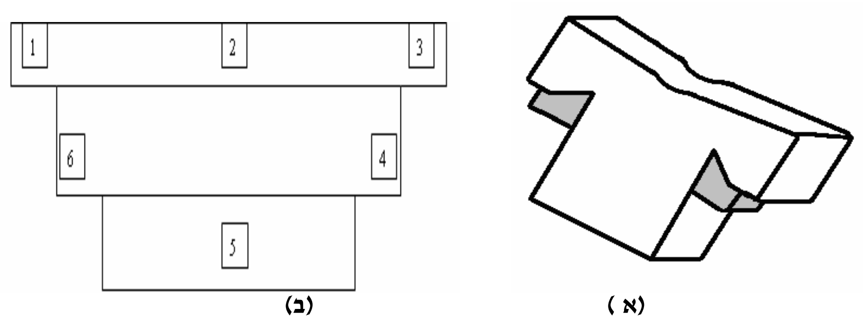
ערכו של קבוע החומר?

משימה מספר 5': חישוב קבוע חומר של דגם סיליקון גלילי. מדוד מימדי הדגם באמצעות סרגל/קליבר. בדוק את הדגם באמצעות גשש K2G. חשב קבוע החומר עבור סיליקון.
מהי ההשפעה של משיכות החומר על ערכו של קבוע החומר?

משימה מספר6: קביעת מהירות הקול בחומר מסוים על פי מימדי הדגם.
קבל מהמדריך 3 דגמים גליליים עשויים פלדה, אלומיניום ונחושת.
מדוד מימדי הדגמים באמצעות סרגל/קליבר. בדוק את הדגמים באמצעות מתמר.
עבור דגם האלומיניום, קבע קבוע החומר. עבור דגמי הפלדה והנחושת מהי מהירות הקול בחומר, באם התקבלה סטייה בתוצאות הסבר מהיכן היא נובעת.

משימה מספר 7: השפעת גודל הגרעינים בדגם פליז על הבדיקה האולטראסונית.
קבל מהמדריך שלושה דגמי פליז בעלי גודל גרעינים ממוצע שונה:
G:1-4=0.06mm, G:2-3=0.21mm, G:3-5=0.36mm , את כל אחד מהדגמים בדוק באמצעות 3 מתמרים בעלי תדירויות: 2MHz, 4MHz, 6MHz. כיצד משתנה עוצמת הסיגנל שמתקבלת עם השינוי בגודל הגרעינים בדגם ובתדירות המתמר? איזו תופעה מבטאת התוצאה שהתקבלה?

משימה מספר 8: בדיקת פורוזיביות ביציקת אלומיניום.
קבל מהמדריך דגם אלומיניום יצוק, מדוד את הדגם באמצעות סרגל/קליבר, בדוק את הדגם באמצעות מתמר K2G ב-6 הנקודות המסומנות באיור 1. ציין באם התקבל סיגנל, במידה ולא התקבל הסבר מה הסיבה לכך.
יש להשוות לתצלום הרדיוגרפי של הדגם. לאיזו שיטת בדיקה יש עדיפות במקרה זה?



(ב) (א)

איור 1: דגם יצוק מאלומיניום (א), והאזורים שיש לבצע בהם בדיקה (ב)

משימה מספר 9: קביעת מיקום פגם במוצר.
קבל מהמדריך דגם גליל אלומיניום יצוק. מדוד גובה הדגם באמצעות סרגל/קליבר.בדוק את הדגם באמצעות מתמר אורכי K2G. השווה לצילום רדיוגרפי של דגם זה וקבע: היכן ממוקם

הפגם, מה צורתו של הפגם. ציין את היתרונות והחסרונות בבדיקה של הדגם הזה בכל אחת מהשיטות . לאיזו שיטת בדיקה יש עדיפות במקרה זה?

<u>משימה מספר 10:</u> קביעת סוג החומר ומיקום פגם במוצר.

קבל מהמדריך2 דגמים גליליים : דגם א' (לא מסומן) לא פגום, דגם ב' מסומן (פגום). מדוד את גובה הדגמים באמצעות סרגל/קליבר. בדוק את הדגמים באמצעות מתמר K2G .

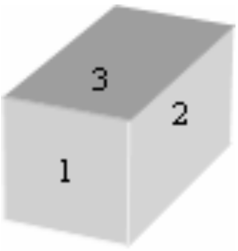
א. קבע MTVEL, ומצא מהו החומר ממנו עשוי הדגם.

ב. השווה לצילום רדיוגרפי של דגם זה וקבע מיקומו של הפגם בדגם ומה עובי הפגם.

<u>משימה מספר 11:</u> - בדיקת אולטראסוניקה בדגם בעל למינציה.

קבל מהמדריך תיבת מגנזיום. מדוד את התיבה באמצעות סרגל/קליבר. בדוק את התיבה באמצעות מתמר K2G ב-3 מפאותיה (ראה איור 2), פרט באם התקבל סיגנל.

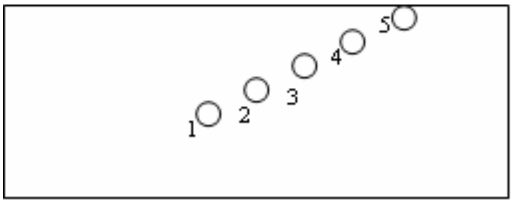
הסבר את התוצאות שמתקבלות.



איור 2: תיבת מגנזיום

<u>משימה מספר 12 (א):</u> בדיקת עומק

קבל מהמדריך תיבת פלדה בעלת סדרה של 5 קדחים בעלי קוטר ועומק שווה (ראה איור 3). מדוד גובה התיבה באמצעות סרגל/קליבר. באמצעות מתמר SEB4 מדוד מרחקי הקדחים מהפאה העליונה ב-6 מיקומים שונים : מעל כל אחד מהקדחים ובחומר עצמו.



איור 3: תיבת פלדה בעלת סדרה של קדחים

מהו גבול הגילוי של הבדיקה האולטרסונית באמצעות מתמר זה? האם הבדיקה זיהתה את כל הקדחים? הסבר.

<u>משימה מספר 12 (ב):</u>

קבל מהמדריך דגם מדרגות אלומיניום. בשלב ראשון מדוד גובה כל אחת מהמדרגות באמצעות סרגל/קליבר ולאחר מכן באמצעות מתמר D-706 . מהו גבול הגילוי של הבדיקה האולטרסונית

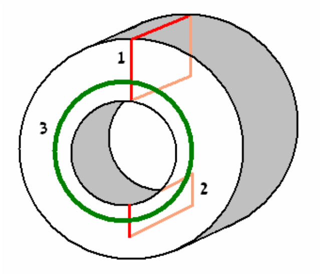
באמצעות מתמר זה? האם תוצאות המדידה הידנית של הגובה תאמו את תוצאות הבדיקה האולטרסונית עבור כל אחת מהמדרגות? הסבר.

משימה מספר 13: זיהוי פגמים בדגם עגול.

קבל מהמדריך דגם פלדה חלול. מדוד עובי הדגם באמצעות סרגל/קליבר. בדגם מצויים פגמים משלושה סוגים: פגם 1: חתך מלא לעומק הטבעת, פגם 2: חתך חלקי בפני שטח הטבעת, פגם 3: פגם רדיאלי, חתך מעגלי לאורכה של הטבעת.

השתמש במתמר SEB4 המוצמד בעזרת מתאם פרספקס הטבול בגליצרין לפני שטח הדגם ובצע בדיקה באזור של כל אחד מהפגמים.

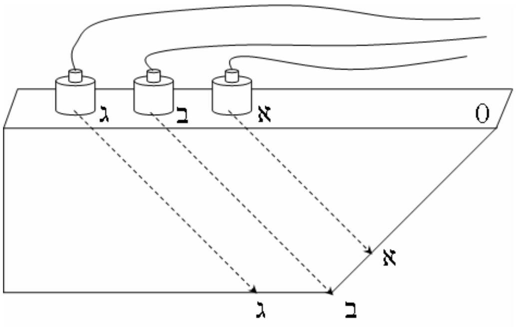
תאר את הסיגנל שמתקבל בכל אחד מהאזורים. באם לא התקבל סיגנל הסבר מדוע.



איור 4: דגם גלילי חלול בעל פגמים

משימה מספר 14 : הכרת המתמר הזוויתי 45°.

קבל מהמדריך דגם פלדה בצורת טרפז בעל זווית בסיס 45° (ראה איור 5). מדוד עובי הדגם באמצעות סרגל/קליבר.

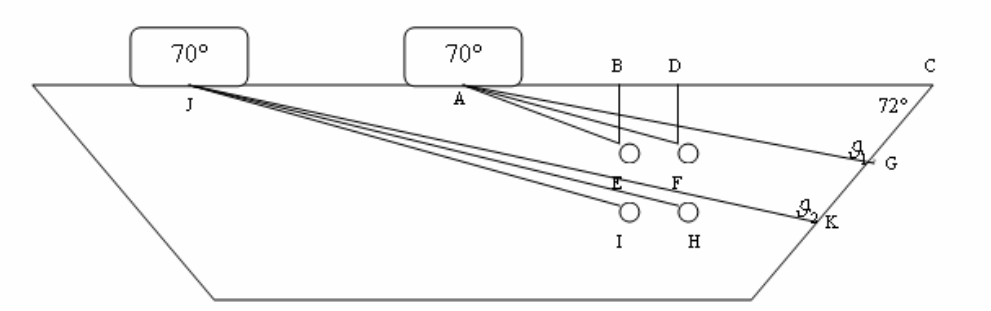


איור 5: דגם פלדה בצורת טרפז בעל זווית בסיס 45°

משימה מספר 15 : הכרת המתמר הזוויתי 70° וזיהוי פגמים מעגליים בדגם.

קבל מהמדריך דגם אלומיניום בצורת טרפז בעל זווית בסיס עליונה של 72°. מדוד עובי הדגם באמצעות סרגל/קליבר. בדגם מצויים ארבעה קדחים כמתואר באיור 6. מיקום הקדחים בדגם

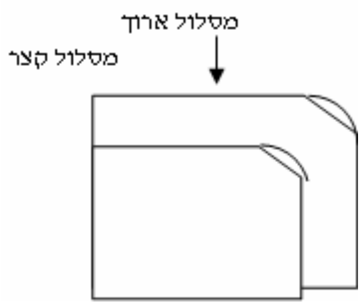
נתון. מדוד באמצעות מתמר זוויתי WB70-2 בנק׳ A ובנק׳ J וקבע על סמך המדידות מהן הזוויות האפשריות בהן נשלח הגל לתוך החומר.



איור 6: דגם אלומיניום בצורת טרפז

משימה מספר 16: הכרת גלי Rayleigh.

קבל מהמדריך דגם פלדה בעל שני מסלולים (כמתואר באיור 7) אשר מידותיו נתונות. השתמש מתמר WB70-2 המוצמד בעזרת מתאם פרספקס הטבול בגליצרין לפני שטח הדגם ובצע מדידה של האורך של כל אחד מהמסלולים. קבע מהירות הגל הנע בחומר זה.



איור 7: דגם פלדה בעל שני מסלולים

5. הנחיות לדו״ח המסכם.

1. הדו״ח המסכם יוכן בהתאם לפורמט המופיע בתחילת ספר המעבדה.
2. תאר את תצפיותייך בכל חלקי הניסוי.
3. השווה בין הבדיקה האולטרסונית לבדיקה הרדיוגרפית כבדיקה ללא הרס.

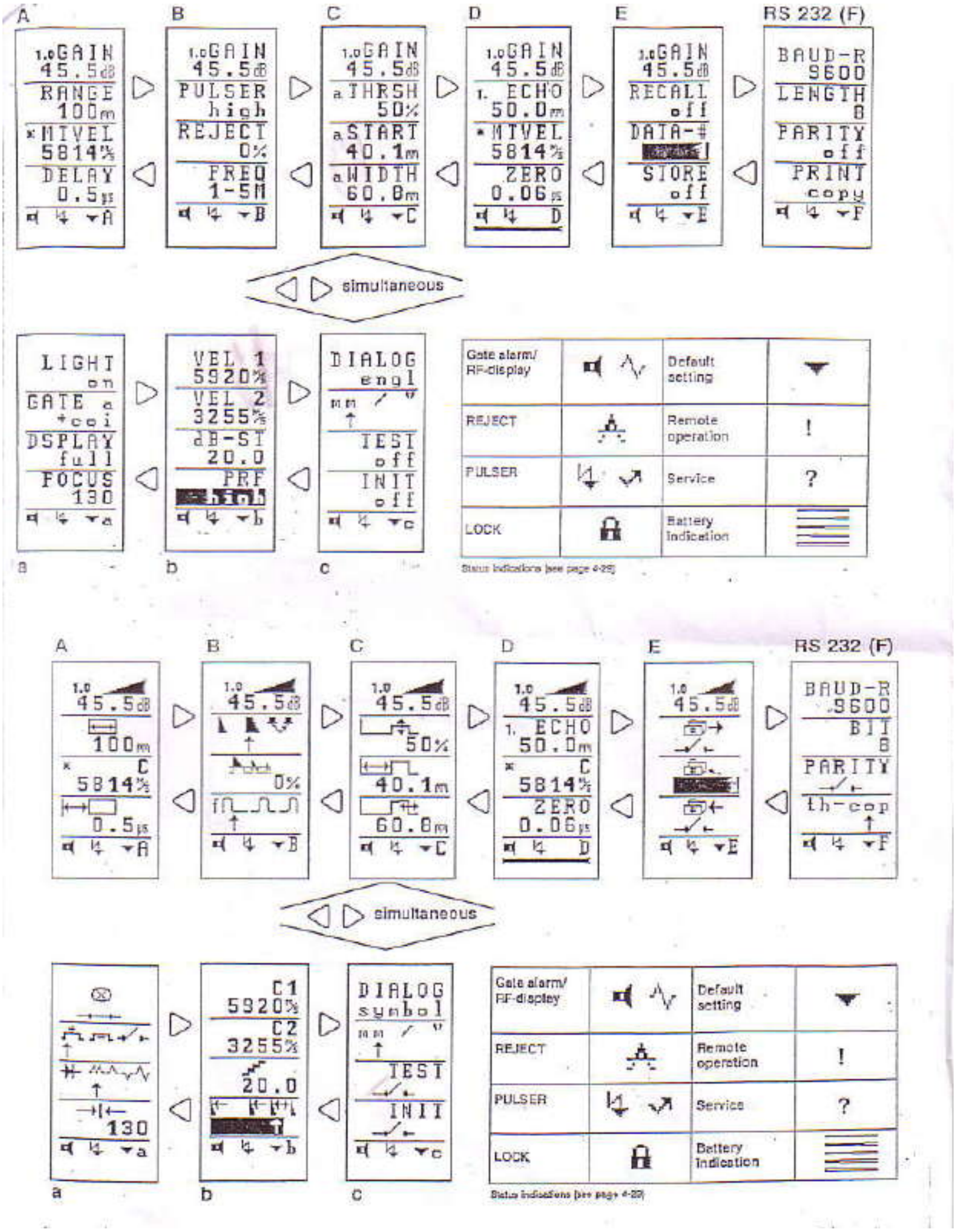
6. ביבליוגרפיה

1. http://www.ndt-ed.org/EducationResources/CommunityCollege/communitycollege.htm
2. קובץ ניסיונות מעבדות שנה ד', הנדסת חומרים, 2007-2008, עמ' 93-129
3. "Handbook of nondestructive evaluation", Charles J. Hellier, 2001 (TA 417.2.H45),
4. "Introduction to the non-destructive testing of welded joints", R. Halmshaw, 1996 (TA 492.W4H3555).
5. "Non destructive evaluation: a tool in design, manufacturing, and service", Don E.Bray, 1997 (TA 417.2.B63).
6. "Metals Handbook", 10th ed., ASM , Vol.17 , Non Destructive Evaluation and Quality Control, 1990 (TA 459 A5).

**נלקח מקובץ ניסיונות מעבדות שנה ג', הנדסת חומרים, 2007-2008.

7. נספחים**

חלק א': דפי עזר למשימות



איור 8: דף עזר למשימה 2

Material Sound velocity	Wave length in mm at frequencies of:						
	0,5 MHz	1 MHz	2 MHz	4 MHz	12 MHz	5 MHz	6 M
Oil, long 1.330 km/s	2.66	1.33	.67	.33	.11	.27	.22
Water, long 1.480 km/s	2.96	1.48	.74	.37	.12	.30	.25
Glycerin, long 1.920 km/s	3.84	1.92	.96	.48	.16	.38	.32
Epoxy resin, long 2.540 km/s	5.08	2.54	1.27	.64	.21	.51	.42
Plexi glass, long 2.730 km/s	5.46	2.73	1.37	.68	.23	.55	.46
Copper, trans 2.260 km/s	4.52	2.26	1.13	.57	.19	.45	.38
Copper, long 4.700 km/s	9.40	4.70	2.35	1.18	.39	.94	.78
Steel, trans 3.250 km/s	6.50	3.25	1.63	.81	.27	.65	.54
Steel, long 5.920 km/s	11.84	5.92	2.96	1.48	.49	1.18	.99
Aluminium, trans 3.130 km/s	6.26	3.13	1.57	.78	.26	.63	.52
Aluminium, long 6.300 km/s	12.60	6.30	3.15	1.58	.53	1.26	1.05

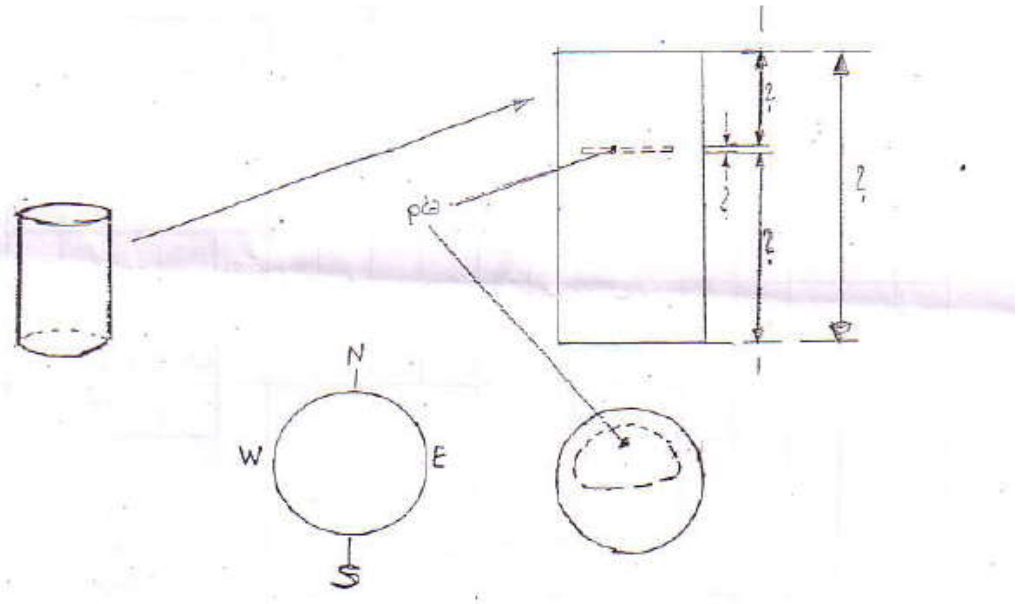
Table V GRAIN SIZE AND HARDNESS OF ALUMINIUM BRASS

CODE	BATCH*	AV. GRAIN DIA.—MM.		$\frac{1}{\sqrt{\text{GRAIN DIA.}}}$	HARDNESS—DPN 20KG		
		(1)†	(2)†		MIN.	MAX.	AV.
G1	1	0.03+	**0.03**	5.8	74	81.5	**77**
G1	2	0.08	**0.08**	3.5	65	76.5	**68**
G1	3	0.035	**0.036**	5.3	72.5	80	**76**
G1	4	0.06	**0.06**	4.1	66	75.5	**70.5**
G1	5		**0.045**		70	78	**74**
G2	1	0.14	**0.14**	2.7	56	65.5	**60**
G2	2	0.15	**0.12**	2.9	56.5	71	**60**
G2	3	0.20	**0.21**	2.2	52.5	62.5	**56**
G2	4	0.20	**0.18**	2.3(5)	54	63	**57**
G2	5		**0.28**		51	60	**55**
G3	1	0.60	**0.53**	1.37	47	57	**51.5**
G3	2	0.50	**0.45**	1.5	49.5	61.5	**52**
G3	3	0.55	**0.50**	1.4(1)	49.5	54	**51.5**
G3	4	0.50	**0.47**	1.4(3)	48	57	**52**
G3	5		**0.36**		48	58	**52.5**

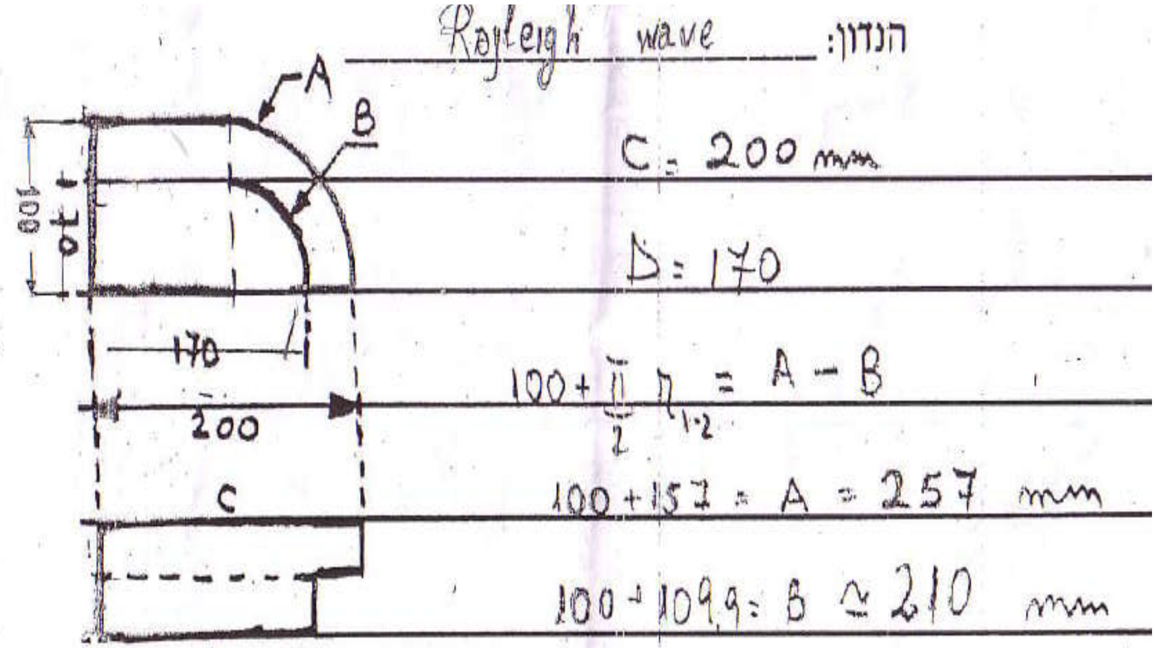
* At this stage, it is felt that the quoted batches cover the range of possibilities, but in the event of further variations, subsequent batch details will be introduced into Table V.

† (1) By comparison. (2) By intercept method—dia. $= 1/N_L$.

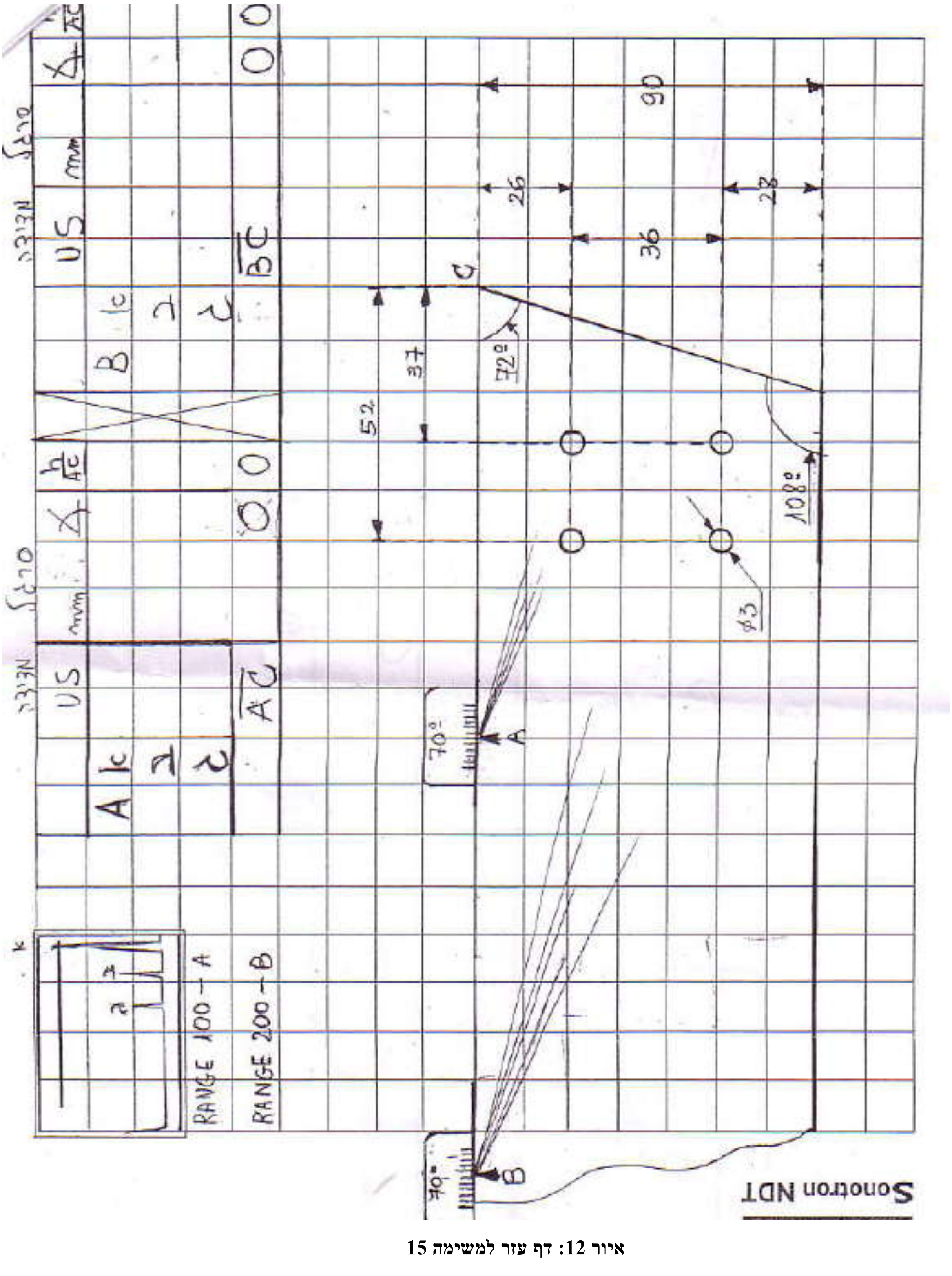
איור 9: דפי עזר למשימה 7



איור 10: דף עזר למשימה 10

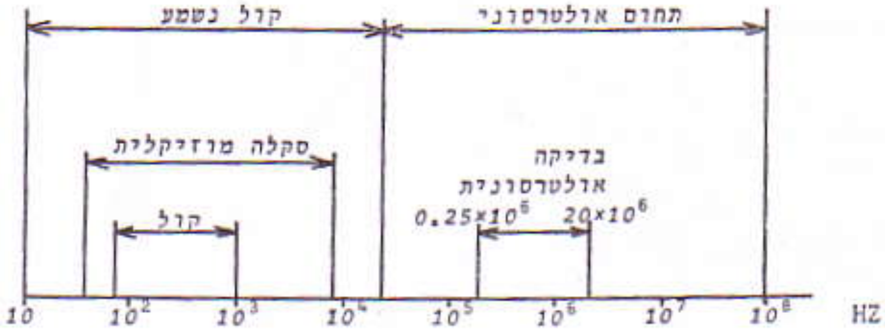


איור 11: דף עזר למשימה 16

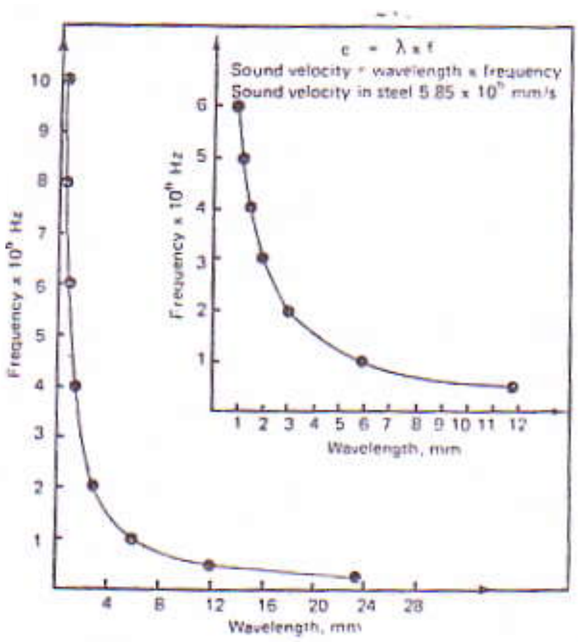


איור 12: דף עזר למשימה 15

חלק ב׳:טבלאות נתונים רלוונטיות



איור 13: תחום תדירויות הבדיקה האולטרסונית

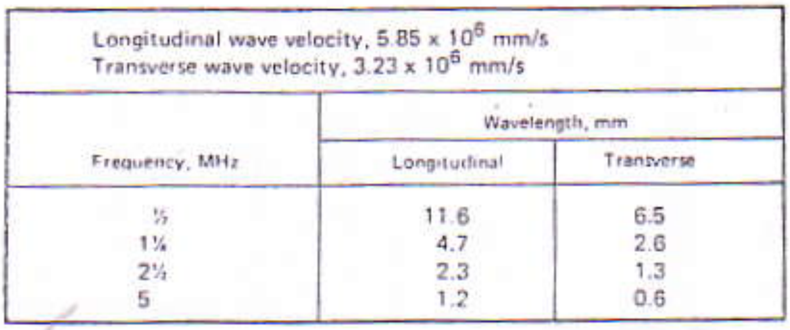


c- מהירות גלי קול (מ"מ/שניה)

f- תדירות (HZ)

λ- אורך גל (מ"מ)

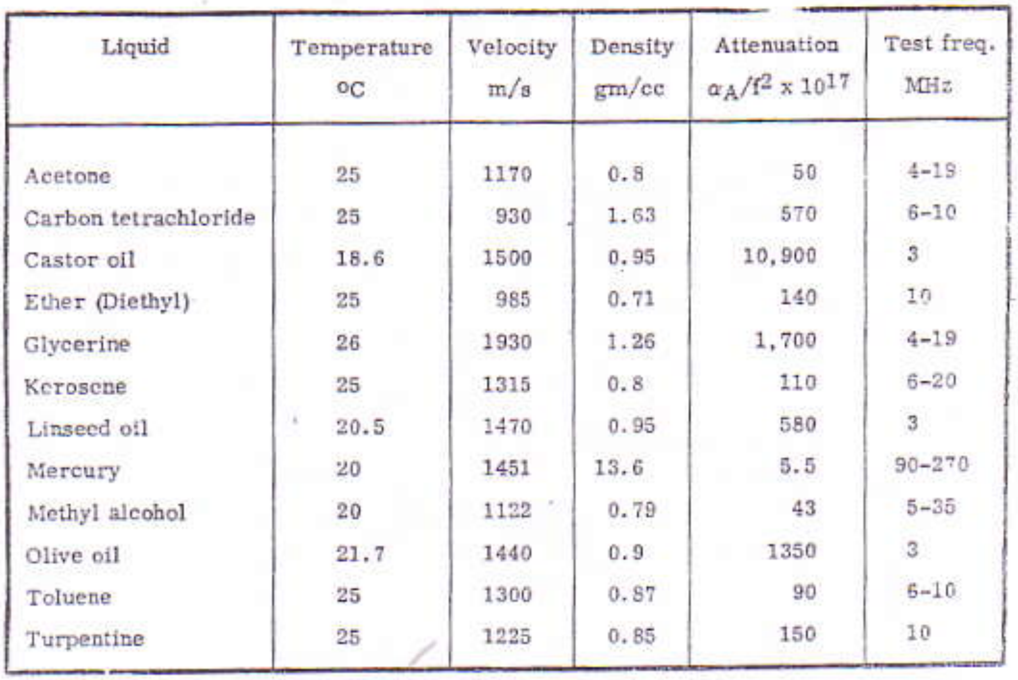
איור 14: יחס בין תדירות לאורך גל בפלדות



Longitudinal wave velocity, 5.85×10^6 mm/s
Transverse wave velocity, 3.23×10^6 mm/s

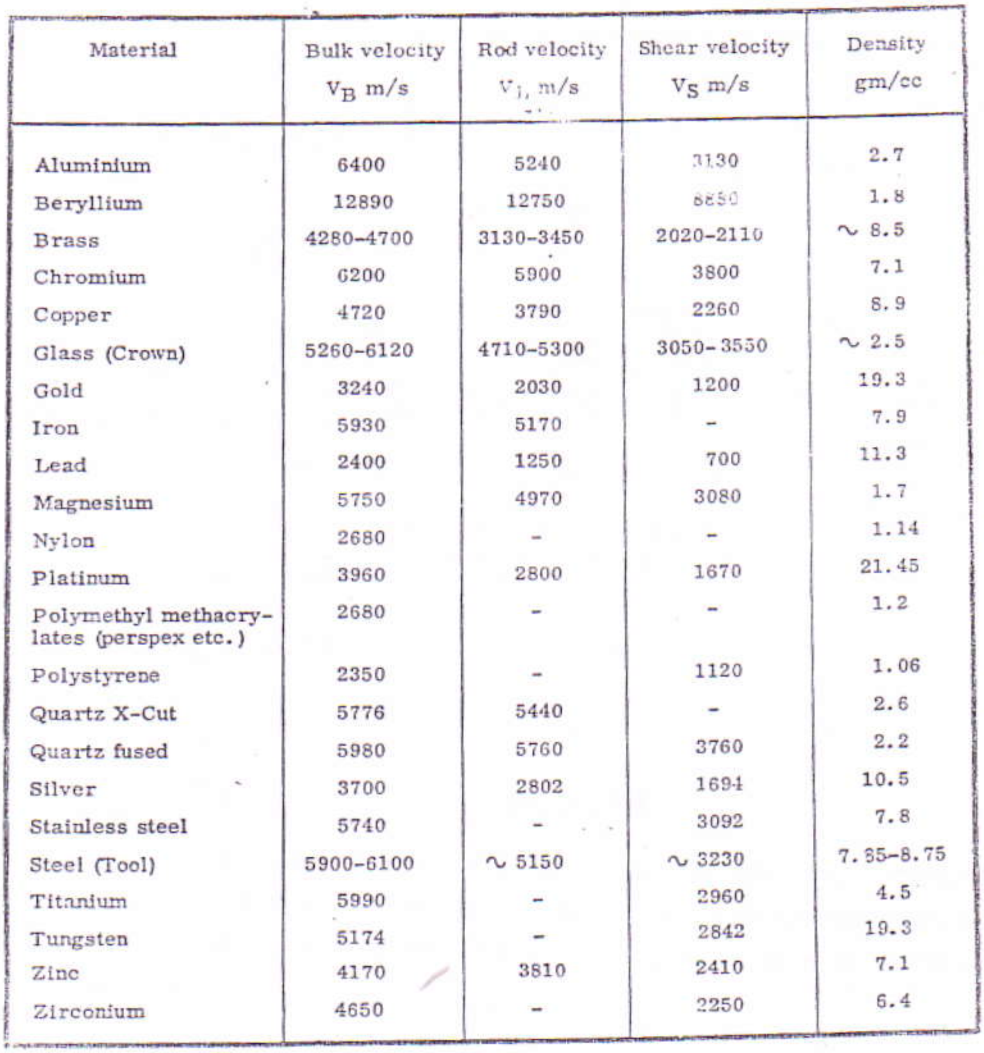
Frequency, MHz	Wavelength, mm	
	Longitudinal	Transverse
½	11.6	6.5
1¼	4.7	2.6
2½	2.3	1.3
5	1.2	0.6

איור 15: מהירות גל קול בפלדה



Liquid	Temperature °C	Velocity m/s	Density gm/cc	Attenuation $\alpha_A/f^2 \times 10^{17}$	Test freq. MHz
Acetone	25	1170	0.8	50	4-19
Carbon tetrachloride	25	930	1.63	570	6-10
Castor oil	18.6	1500	0.95	10,900	3
Ether (Diethyl)	25	985	0.71	140	10
Glycerine	26	1930	1.26	1,700	4-19
Kerosene	25	1315	0.8	110	6-20
Linseed oil	20.5	1470	0.95	580	3
Mercury	20	1451	13.6	5.5	90-270
Methyl alcohol	20	1122	0.79	43	5-35
Olive oil	21.7	1440	0.9	1350	3
Toluene	25	1300	0.87	90	6-10
Turpentine	25	1225	0.85	150	10

איור 16: מהירות והנחתת גלים בנוזלים



Material	Bulk velocity V_B m/s	Rod velocity V_L m/s	Shear velocity V_S m/s	Density gm/cc
Aluminium	6400	5240	3130	2.7
Beryllium	12890	12750	8850	1.8
Brass	4280-4700	3130-3450	2020-2110	∼ 8.5
Chromium	6200	5900	3800	7.1
Copper	4720	3790	2260	8.9
Glass (Crown)	5260-6120	4710-5300	3050-3550	∼ 2.5
Gold	3240	2030	1200	19.3
Iron	5930	5170	-	7.9
Lead	2400	1250	700	11.3
Magnesium	5750	4970	3080	1.7
Nylon	2680	-	-	1.14
Platinum	3960	2800	1670	21.45
Polymethyl methacrylates (perspex etc.)	2680	-	-	1.2
Polystyrene	2350	-	1120	1.06
Quartz X-Cut	5776	5440	-	2.6
Quartz fused	5980	5760	3760	2.2
Silver	3700	2802	1694	10.5
Stainless steel	5740	-	3092	7.8
Steel (Tool)	5900-6100	∼ 5150	∼ 3230	7.85-8.75
Titanium	5990	-	2960	4.5
Tungsten	5174	-	2842	19.3
Zinc	4170	3810	2410	7.1
Zirconium	4650	-	2250	6.4

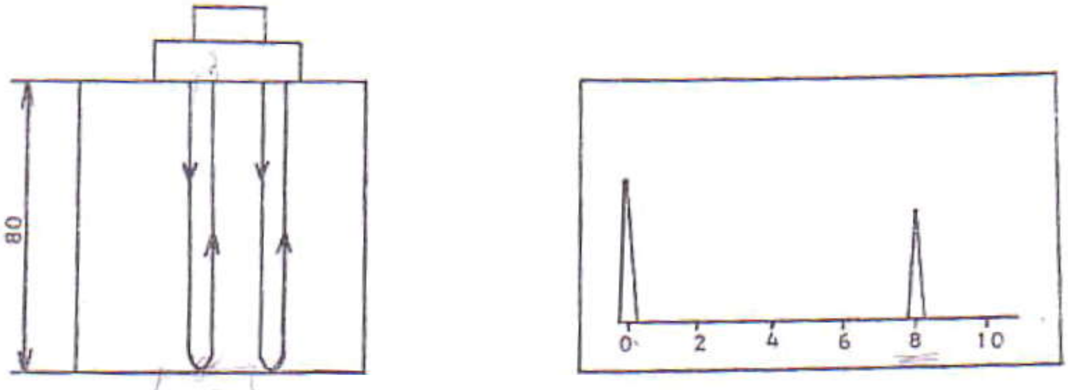
איור 17: מהירות גלי קול במוצקים

Material	Sound velocity (longitudinal), mm/s $\times 10^6$ (c)	Density, gm/mm$^3 \times 10^{-3}$ (ρ)	Acoustic impedance c.g.s. units $\times 10^4$ (ρ.c.)
Steel	5.85	7.8	4.56
Oil	1.38	0.92	0.127
Water	1.49	1.0	0.149
Air	0.33	0.0013	0.000043
Glycerine	1.90	1.26	0.239
Perspex	2.70	1.20	0.324

איור 18: מהירות גלי קול, צפיפות ועכבה אקוסטית במוצקים שונים

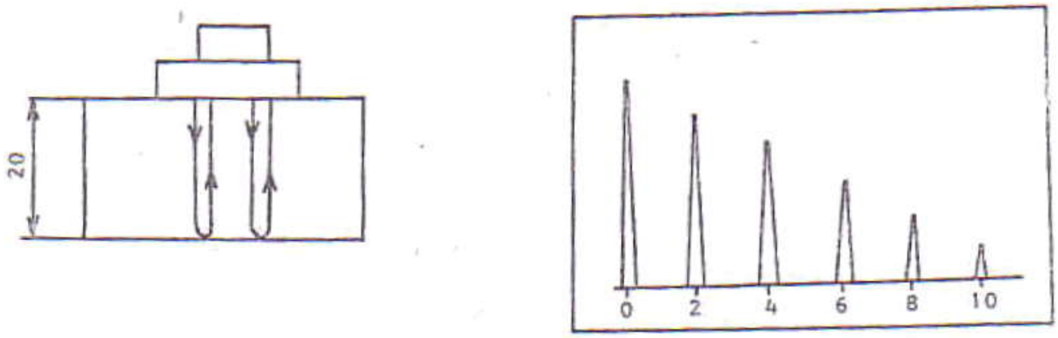
חלק ג׳:שיטות בדיקה אולטרסוניות

כאשר המתמר משדר גל קול מתקבל החזר ראשון מפני השטח הנבדק. החזר נובע משכבת נוזל דקיקה ליצירת מגע נאות בין המתמר לשטח הנבדק (איור 19).



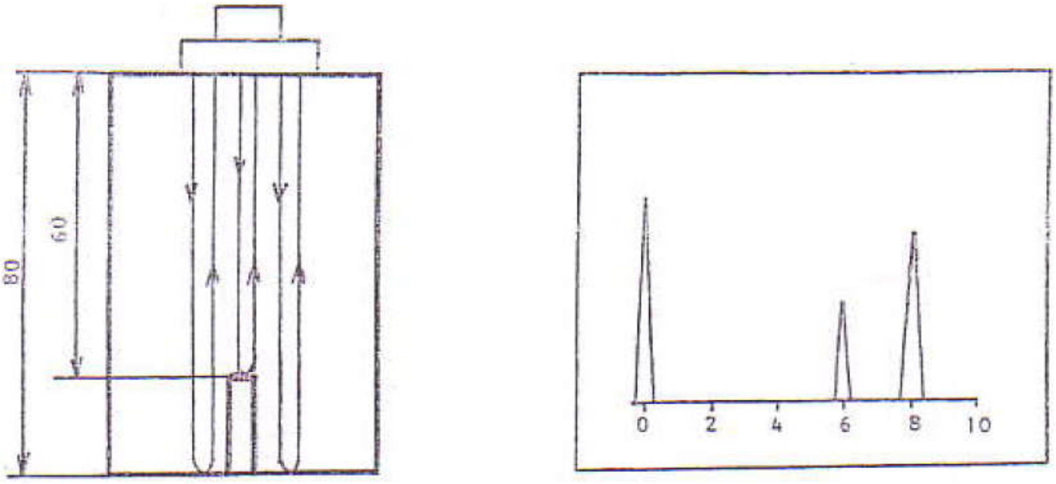
איור 19: דגם ללא פגם

את ההחזר הראשוני מפני השטח הנבדק יש לאפס על המסך. החזר נוסף יתקבל מסוף הדגם.
כאשר בודקים דגם בעל עובי קטן יתכן ויתקבלו החזרים נוספים מסוף הדגם (איור 20). ככל שגל הקול נע מרחק גדול יותר בתוך החומר כך עוצמתו תחלש ואכן גל המוחזר מסוף הדגם בפעם הראשונה עוצמתו גדולה מגל המוחזר שנית מסוף הדגם. ככל שההחזרים רבים יותר כך עוצמתם קטנה.

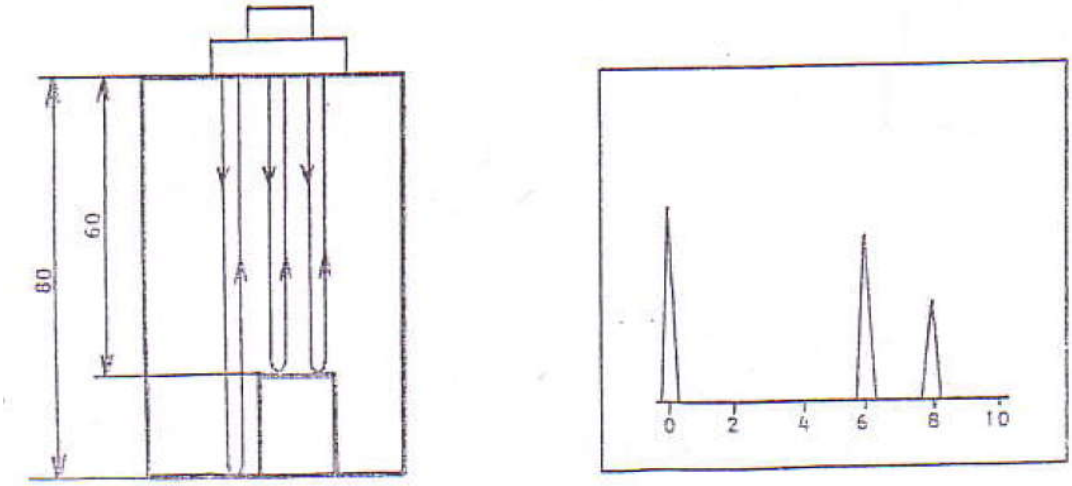


איור 20: דגם בעל עובי קטן

בדגם עם פגם יתקבל על המסך החזר ראשון מפני השטח. החזר שני מהפגם והחזר שלישי מסוף הדגם (איור 21). ככל שהפגם גדול יותר ההחזר ממנו יהיה בעל עוצמה גדולה יותר (איור 22).

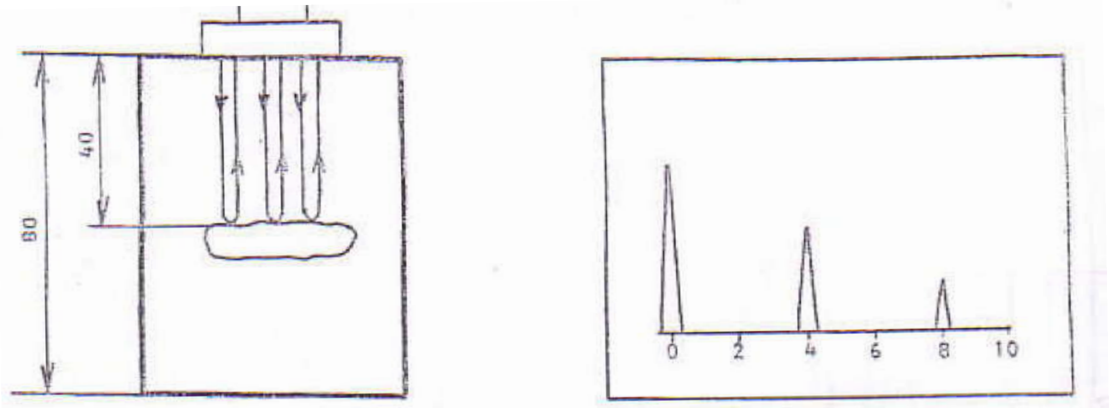


איור 21: דגם עם פגם



איור 22: דגם עם פגם גדול יותר

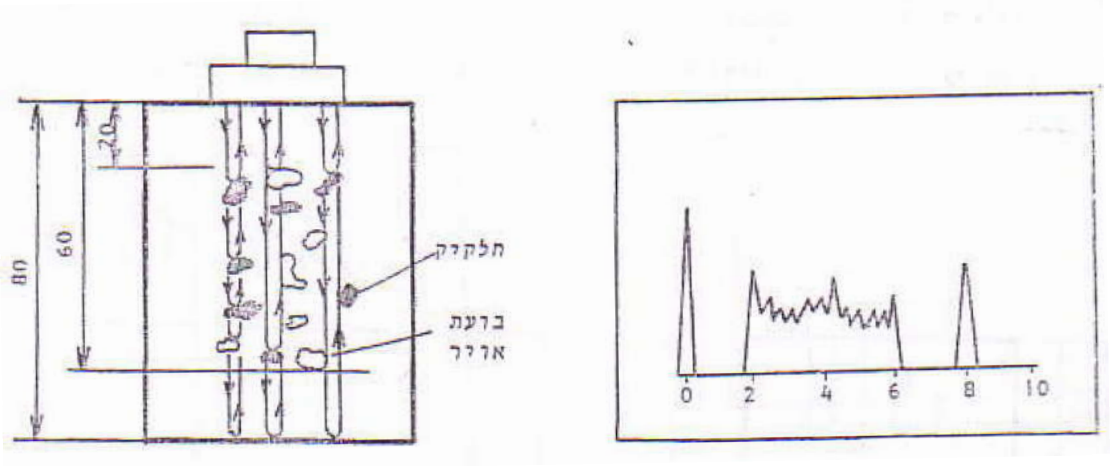
בדגם עם פגם גדול במרכזו:



איור 23: דגם עם פגם גדול במרכזו

ההחזר כולו יהיה מהפגם. החזר ראשון יתקבל מפני שטח הדגם, החזר שני יהיה מהפגם והחזר שלישי לא יהיה מסוף הדגם אלא החזר שני מהפגם במרכז הדגם (איור 23).

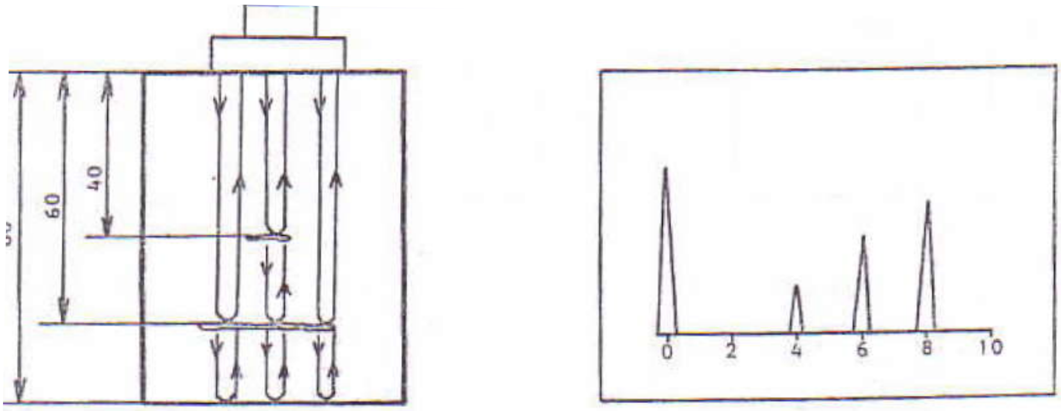
בדגם עם פגם בצורת חלקיקים זעירים או בועות אוויר בתוך הדגם:



איור 24: דגם עם פגם בצורת חלקיקים זעירים

החזר ראשון מפני שטח הדגם. החזרים נוספים יתקבלו מבועות האוויר או מהחלקיקים הקטנים בתוך הדגם (איור 24). החזר מבועת אוויר גדול יותר בעוצמתו מההחזר מחלקיק זר.
בתוך החומר גל הקול אינו יכול להמשיך בתווך שהוא גז או אוויר ולכן הוא מוחזר כולו. לעומתו גל הקול הפוגע בחלקיק יכול להמשיך דרכו וההחזר ממנו יהיה קטן. החזר שלישי יתקבל מסוף הדגם.

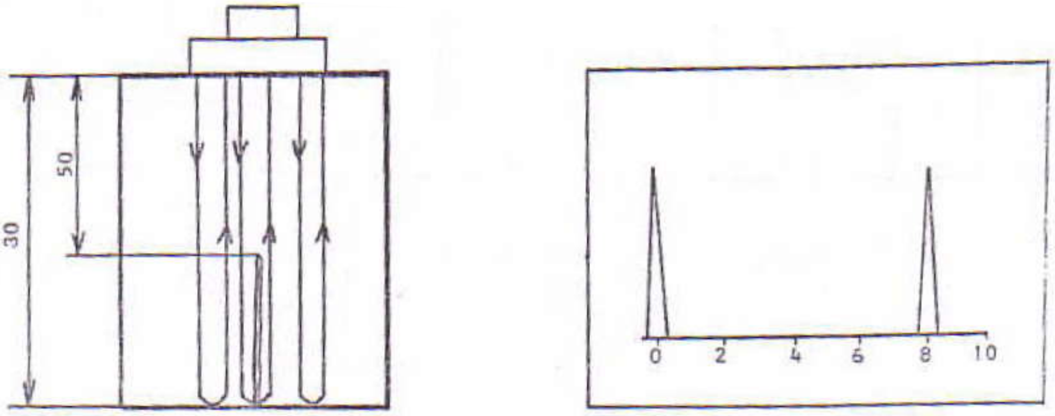
בדגם עם פגמי סדקים לרוחב הדגם:



איור 25: דגם עם פגמי סדקים לרוחב הדגם

החזר ראשון יתקבל מפני שטח הדגם. החזר שני מפגם קטן במרכז הדגם. החזר שלישי מהפגם הגדול הקרוב לתחתית הדגם, גם ההחזר ממנו גדול יותר והחזר רביעי מסוף הדגם הנבדק (איור 25).

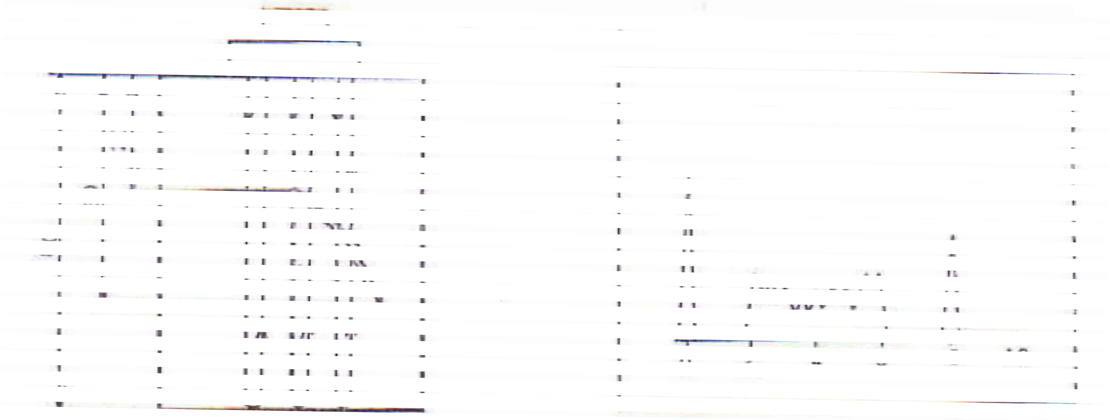
בדגם עם סדק אורכי:



איור 26: דגם עם סדק אורכי

החזר ראשון יתקבל מפני שטח הדגם והחזר שני יתקבל מסוף הדגם (איור 26). הגשש לא יגלה את הסדק האורכי מאחר וההחזר ממנו כה זעיר שלא ניתן לגלותו על המסך.

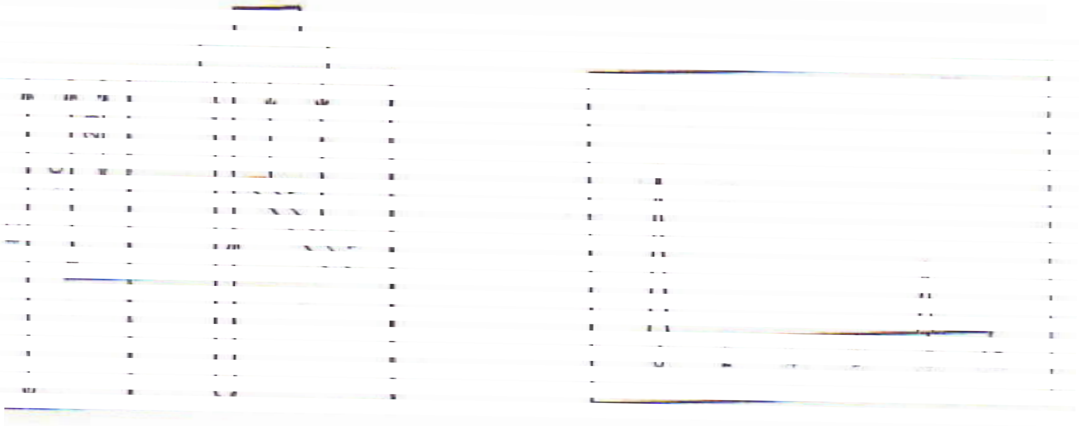
בדגם עם פגם בצורת סדק אלכסוני:



איור 27: דגם עם פגם בצורת סדק אלכסוני

החזר ראשוני יתקבל מפני שטח הדגם הנבדק. החזרים נוספים יתקבלו מהסדק כאשר החזר הגדול בעוצמתו יתקבל משטח הסדק המקביל לשטח הנבדק, החזר אחרון יהיה מסו הדגם הנבדק (איור 27).

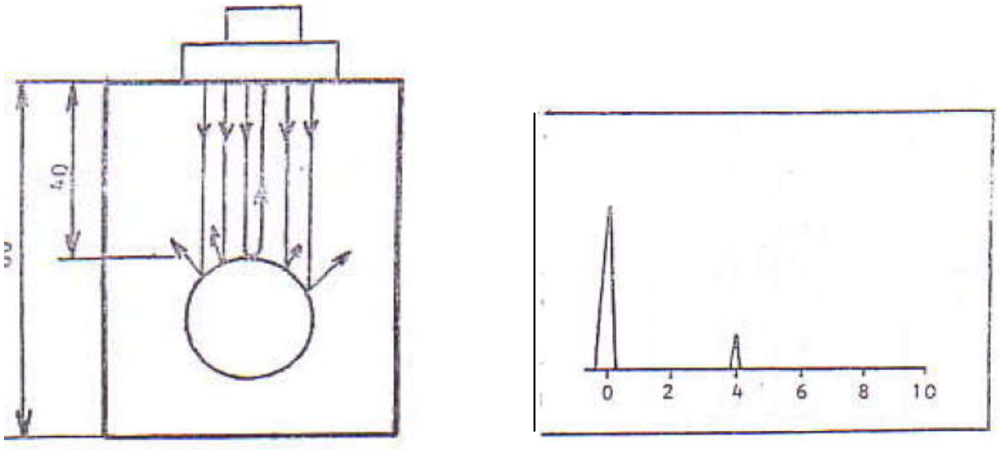
בדגם עם פגם אלכסוני:



איור 28: דגם עם פגמי סדקים לרוחב הדגם

החזר ראשוני יתקבל מפני שטח הדגם הנבדק. החזר נוסף יתקבל מסוף הדגם אך בעוצמה חלשה עקב פיזור רוב עוצמת גלי הקול הפוגעים בסדק ומתפזרים בתוך הדגם (איור 28).

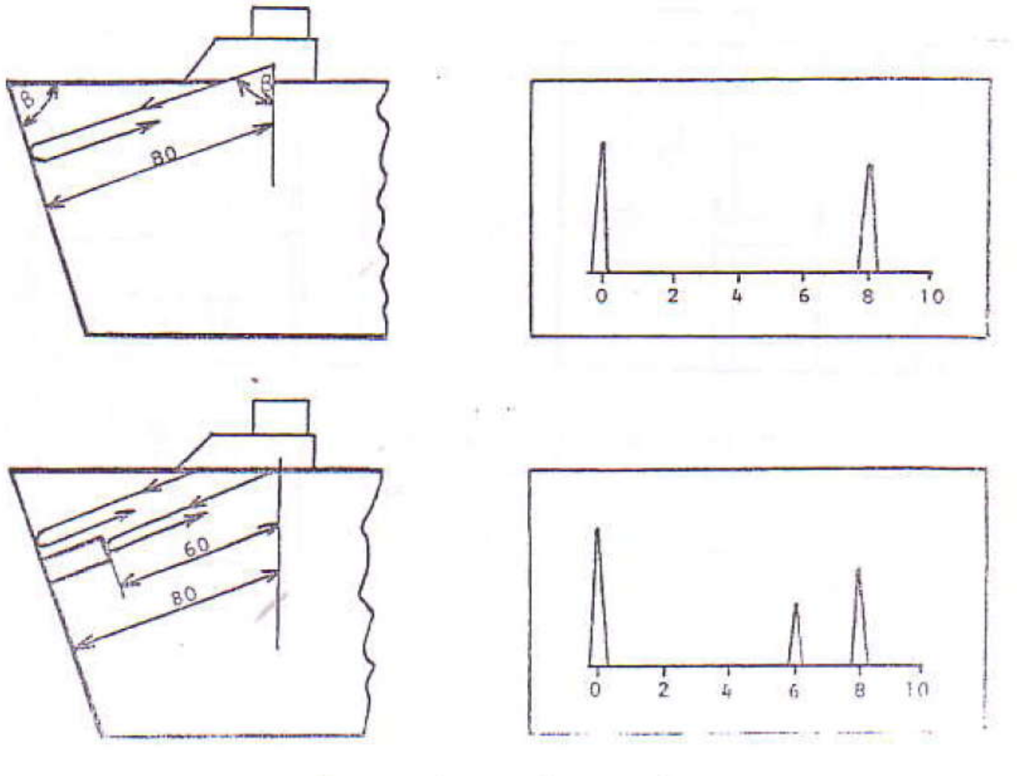
בדגם עם פגם כדורי:



איור 29 : דגם עם פגם כדורי

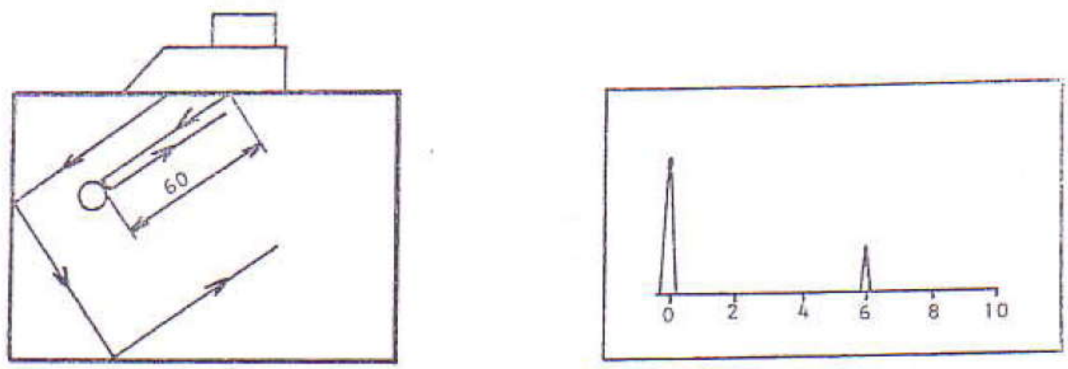
החזר ראשוני מתקבל מפני שטח הדגם. החזר שני קטן בעוצמתו מוחזר מהפגם עקב הפיזור העצום של גלי הקול בדגם. פגם זה אופייני לבועות אוויר בתוך החומר (איור 29).

בדיקות במתמרים זוויתיים:



איור 30: בדיקות במתמרים זוויתיים

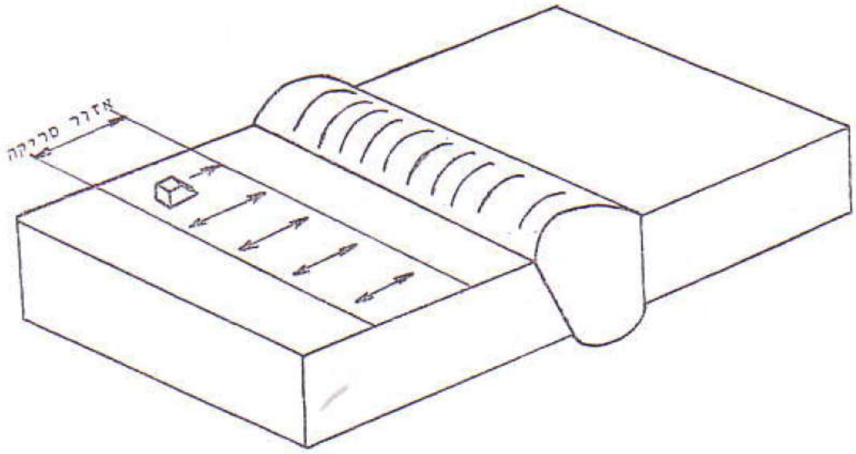
החזר ראשון מתקבל מפני השטח הנבדק, החזר נוסף מהפגם ועוצמתו תלויה בגודל הפגם, החזר שלישי מסוף הדגם (איור 30).



איור 31: בדיקה במתמר זוויתי של דגם עם פגם במרכזו

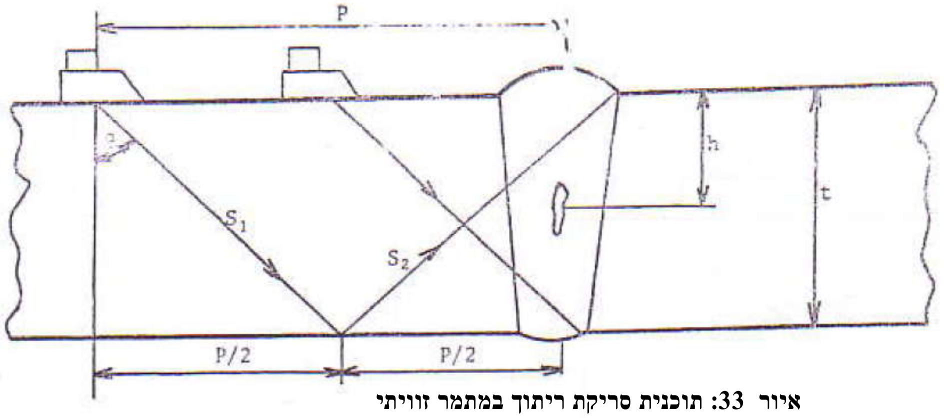
בדגם עם פגם במרכזו יתקבל החזר ראשון מפני השטח הנבדק, החזר שני מהפגם. לא יתקבל החזר נוסף מסוף הדגם בגלל פיזור גלי הקול בחומר (איור 31).

שימוש נרחב במתמר זוויתי נעשה בבדיקות ריתוך. בריתוך קיימת עקמומיות מעל פני השטח ולכן לא ניתן לבדוק עם מתמר רגיל (איור 32).



איור 32: שימוש במתמר זוויתי בבדיקות ריתוך

בבדיקות ריתוך חייבים לתכנן תוכנית סריקה של הגשש שתבדוק את כל גובה הריתוך (איור 33).



איור 33: תוכנית סריקת ריתוך במתמר זוויתי

$p = S \cdot \sin\beta$,

$p/2 = t \cdot tg\beta$,

במקרה של החזרה אחת: $h = S \cdot \cos\beta$,

במקרה של החזרה+שבירה: $h = 2t - S \cdot \cos\beta$

β – זווית הגל שנשלחת מהמתמר.

P- מרחק מתמר מהריתוך.

S=S1+S2- אורך מעבר גל קול (מתקבל על המסך)

h- גובה הפגם

t- עובי הריתוך

מרחק סריקה היא תנועת הגשש מנקודה P בה מתקבל החזר מהחלק העליון של הריתוך ועד לנקודה P/2 בה מתקבל החזר מתחתית הריתוך. כך ניתן לסרוק את כל גובה הריתוך כך שבמקרה ומתגלה פגם ניתן לדעת בוודאות את גודלו ומיקומו בתוך הריתוך (איור 28).

תוכנית הסריקה בעזרת מתמר זוויתי תעשה בין נקודות P ל-P/2 ולאורך כל הריתוך כאשר תנועת המתמר מנקודה P לנקודה P/2.