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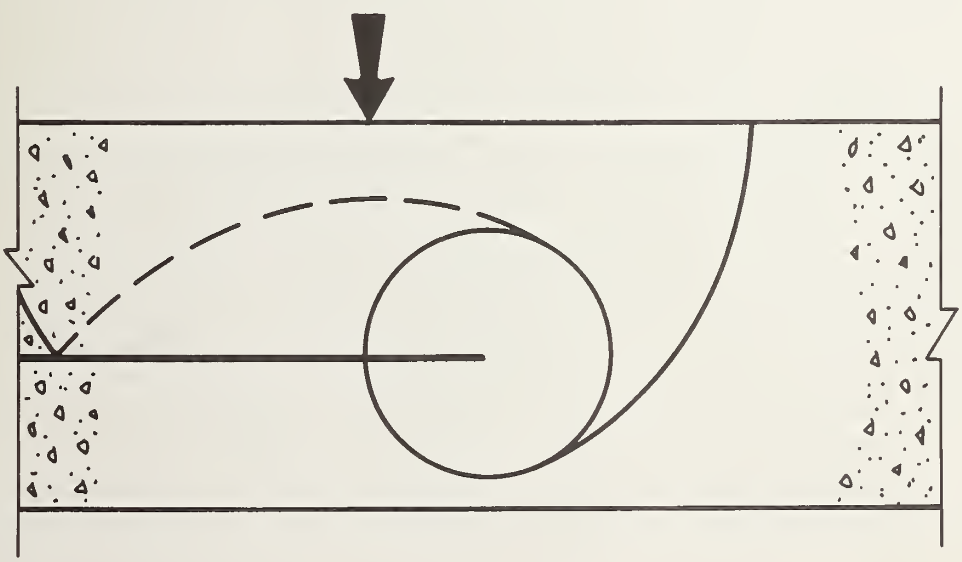
Pulse-Echo Method for Flaw Detection in Concrete



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Nicholas J. Carino
Mary Sansalone

Structures Division
Center for Building Technology
National Engineering Laboratory
National Bureau of Standards
Gaithersburg, Maryland 20899

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

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PULSE-ECHO METHOD FOR FLAW DETECTION IN CONCRETE

Nicholas J. Carino and Mary Sansalone

National Bureau of Standards
Washington, D.C. 20234

The basic principles of the pulse-echo method for the detection of internal flaws in concrete are presented. As the heterogeneous nature of concrete poses problems not encountered in pulse-echo evaluation of metals, progress in this area of concrete nondestructive testing has been slow. A review of past research shows that pulse-echo techniques have been used successfully to detect flaws within concrete; however, no standardized method currently exists for pulse-echo evaluation of concrete structures. Based on the current state of knowledge, areas of needed research are outlined.

Keywords: Acoustics; concrete; integrity testing; nondestructive testing; pulse-echo method; wave propagation.

1. INTRODUCTION

Despite recent advances in concrete technology, there is no satisfactory method for detecting internal defects in hardened concrete. The need for this capability is increasing with the current emphasis on rehabilitation of existing structures and on quality acceptance systems for new construction. The routine method for verifying the existence of defects within a concrete structure is the taking of drilled core samples. This approach has several disadvantages: 1) it is expensive; 2) it is destructive and requires subsequent repair of the holes; and 3) it samples only a small portion of the concrete in a structure.

While it is possible to "look" inside concrete using X-ray or gamma radiography, such methods are expensive and cumbersome and they may pose health hazards. Thus, there is an urgent need to develop a reliable nondestructive system for flaw detection that is economical and easy to operate. The pulse-echo method, which is based on the principle that internal defects will interact with stress waves, has the potential to fill this need.

With the exception of visual inspection, the use of acoustic methods is the oldest form of nondestructive testing. Striking an object with a hammer and listening to the "ringing" sound is a common way of detecting the presence of internal voids, cracks or delaminations. This form of acoustic inspection is known formally as "resonant frequency testing." Its disadvantage is that it is primarily a qualitative and subjective test.

With the advent of sophisticated electronic instrumentation in the 1940's, two nondestructive test methods based upon acoustic waves were developed: the through-transmission method and the pulse-echo method. Figure 1 illustrates the basic principles and differences of the two approaches. In the through-transmission method, one measures the time it takes for a pulse, which is defined as a short wave train, to travel from a transmitting transducer to a receiving transducer. From the measured travel time and the known distance between transducers, an apparent pulse velocity is calculated. The computed pulse velocity value can be used to draw inferences about the integrity of the medium. This approach has its limitations: it requires two accessible surfaces and it offers no indication as to the cause of any differences among pulse velocity values in different parts of a structure. In the pulse-echo method both the pulse source and the receiving transducer are mounted on the same surface. The receiver monitors wave reflections from internal defects or external boundaries. One measures the round-trip travel time from the initialization of the pulse to the reception of the reflected pulse. Thus, if the velocity of the pulse is known, the distance to a defect or an interface can be calculated.

The pulse-echo method is commonly used to inspect welds in steel structures for the presence of cracks, porosity, or slag inclusions. Recently medical researchers have used the method to scan the human body, eliminating the need for harmful X-ray analysis. Pulse-echo methods have been used for detecting very large structural cracks in concrete dams, for integrity testing of slender concrete structures, such as piles, and for measuring the thickness of plate elements, such as highway slabs. However, no versatile, standardized method currently exists for general nondestructive evaluation of concrete structures.

The objective of this paper is to provide the reader with background information on the pulse-echo method and its use in the evaluation of concrete structures. We begin with a discussion of the basic principles of elastic wave propagation and reflection and we explain why concrete poses problems not encountered in homogeneous materials, such as metals. This is followed by a review of past research results where pulse-echo techniques were used successfully to evaluate concrete structures. Finally, areas of needed research are outlined.

2. PRINCIPLES OF THE METHOD

The pulse-echo method for nondestructive testing is analogous to the sonar system used by ships for sounding ocean depths. Mechanical energy in the form of a short pulse is introduced into the test medium at an accessible surface by a transmitter. As the resulting stress wave propagates through the medium it is reflected by material defects or by interfaces between phases of different densities or elastic moduli. A receiving transducer coupled to the surface of the test object monitors these reflected waves, or echoes. The transducer output is displayed on an oscilloscope. Using the time base of the display, the travel time of the pulse can be determined. If the wave velocity in the medium is known, the round-trip travel time of each echo can be used to determine the location of a defect or an interface.

2.1 Wave Propagation

When a stress pulse is applied to the surface of an object, the pulse propagates into the object and, at any particular instant, its location can be identified by the wave front. There are three idealized shapes of wave fronts: planar, spherical and cylindrical [1]. The shape of a wave front will depend upon the characteristics of the source that is used to generate the stress pulse. A true plane wave is produced by a flat oscillator that is mounted in a rigid wall and which radiates into a liquid [2]. When a stress pulse is introduced into a solid object using a point source (e.g., by impacting the surface of the object over a small contact area) the resulting wave front is spherical. A cylindrical wave front is generated by a line source; the line forms the axis of the cylindrical wave. The wave fronts of spherical or cylindrical waves diverge as they travel away from their source. However, at far distances from the source the wave fronts of divergent waves become nearly planar, and their acoustic properties become very similar to those of plane waves [2].

2.2 Wave Modes

There are three primary modes of stress wave propagation through isotropic elastic media. These wave modes are characterized by the oscillation path of the particles transmitting the wave. The first mode of vibration is the longitudinal or compression wave mode, in which the particles transmitting the wave vibrate about their equilibrium position in a direction parallel to the direction of wave propagation. Although compression waves (commonly referred to as P-waves) propagate in all types of media, a second mode of vibration, the transverse or shear wave mode, can propagate only in media with shear stiffness, i.e., in solids. In shear waves (S-waves) particle vibration is perpendicular to the direction of wave propagation. Where there is a solid/liquid or a solid/gas interface, Rayleigh or surface waves (R-waves) can propagate over the interface. In this mode of vibration the oscillation path of the particles is elliptic. The amplitude of particle motion in a surface wave decreases exponentially with distance away from a free boundary [3]. Figure 2a illustrates the propagation of the wave fronts corresponding to the three wave modes in a plate. The stress pulse was introduced into the top surface of the plate by a point source; thus the resulting wave fronts of the P and S-waves are spherical.

2.3 Wave Characteristics

The major parameters associated with stress waves, along with their corresponding symbols and units, are given in Table 1. The following relationship between frequency, f, wavelength, λ, and wave velocity, C, is valid for all types of waves.

$$f \lambda = C \tag{1}$$

Other characteristics of stress waves are amplitude of particle motion, A, acoustic pressure, P, and acoustic intensity, I. (Acoustic intensity is the average rate of flow of energy through a unit area normal to the direction of wave propagation [1]). For compression or shear waves, the amplitude of particle motion depends on the intensity and the wavelength of the propagating wave and on the physical properties of the material in which the wave is propagating [4]:

$$A = \sqrt{\frac{\lambda^2 I}{2 \pi^2 \rho C}} \tag{2}$$

where is the mass density of the material. The amplitude of particle motion is extremely small. For a compression wave in concrete, with an intensity of 10 Watts/cm^2 (a very high value for pulse-echo testing of materials [2]), the amplitude of particle motion is on the order of one-thousandth of a millimeter or less. Displacement amplitude is related to acoustic pressure by the following equation [2]:

$$P = \rho C \omega A \tag{3}$$

where ω is the angular frequency of the wave. For compression waves acoustic pressure is the normal stress parallel to the direction of propagation. For shear waves acoustic pressure is the shear stress associated with the propagating wave.

2.4 Wave Velocity

The propagation of stress waves through a heterogeneous bounded solid, such as a structural concrete member, is a complex phenomenon. However, a basic understanding of the relationship between the physical properties of a material and the velocity of wave propagation can be acquired from the theory of wave propagation in infinite isotropic elastic media [5].

In infinite elastic solids the compression wave velocity, C_p, is a function of Young's modulus of elasticity, E, the mass density, ρ, and Poisson's ratio, ν:

$$C_p = \sqrt{\frac{E(1 - \nu)}{(1 - \nu)(1 - 2\nu)}} \tag{4}$$

In bounded solids, such as thin plates or long rods, compression wave velocity can vary depending on the dimensions of the solid relative to the wavelength of the propagating wave. For rod-like structures, such as piles, compression wave velocity is independent of Poisson's ratio if the rod diameter is much less than the wavelength of the propagating wave [4]. In this case C_p is given by the following equation:

$$C_p = \sqrt{\frac{E}{\rho}} \tag{5}$$

For $\nu = 0.2$, a typical value for concrete, the compression wave velocity is five percent higher in an infinite solid than in a long thin rod.

The shear wave the velocity, C_s, in an infinite solid is given by the following equation:

$$C_s = \sqrt{\frac{E}{2\rho(1 - \nu)}} = \sqrt{\frac{G}{\rho}} \tag{6}$$

where G is the shear modulus of elasticity. For $\nu = 0.2$, the shear wave velocity is 61 percent of the compression wave velocity.

Surface waves propagate at a velocity, C_R, which can be determined from the following approximate formula [6]:

$$C_R = \frac{0.87 + 1.12}{1 +} C_s \tag{7}$$

For $\nu = 0.2$, the surface wave velocity is 92 percent of the shear wave velocity.

In many applications compression wave velocity cannot be measured directly. However, compression wave velocity is related to surface wave velocity by the following equation:

$$C_R = \frac{0.87 + 1.12}{1 + \nu} \sqrt{\frac{1 - 2\nu}{2(1 - \nu)}} C_p \tag{8}$$

Thus, if Poisson's ratio is known, the measured surface wave velocity can be used to estimate the compression wave velocity [7]. For $\nu = 0.2$, the surface wave velocity is 56 percent of the compression wave velocity.

2.5 Reflection

When a wave front is incident upon an interface between dissimilar media, "specular" reflection occurs. (The term specular reflection is used since the reflection of stress waves is similar to the reflection of light by a mirror.) Stress waves can be visualized as propagating along ray paths with the geometry of ray reflection being analogous to that of light rays. The shape of the reflected wave front can be determined by considering the reflection of individual rays. In Figure 2b incident rays OA and OB are reflected as rays AC and BD, and it is seen that the reflected rays behave as though they were radiating from virtual point O'. Thus, the reflected wave fronts PP and SS are also spherical.

At a boundary between two different media only a portion of a stress wave is reflected. The remainder of the wave penetrates into the underlying medium (wave refraction), as shown in Figure 3a. The angle of refraction, β, is a function of the angle of incidence, θ, and the ratio of wave velocities, C_2/C_1, in the different media and is given by Snell's Law [8]:

$$\sin \beta = \frac{C_2}{C_1} \sin \theta \tag{9}$$

Unlike other types of waves, stress waves can change their mode of propagation either partially or completely when striking the surface of a solid at an oblique angle [9]. Incident compression waves can be partially reflected as both compression and shear waves and can be refracted as both compression waves and shear waves, or as a surface wave, depending on the angle of incidence. Since shear waves propagate at a velocity less than that of compression waves, they will reflect and refract at angles, θ_S and β_S, that are less than the angles of reflection and refraction of the compression waves, as shown in Figure 3b.

The relative amplitude of reflected echoes depends on the mismatch in specific acoustic impedances at an interface, the angle of incidence, the size, shape, and orientation of a flaw or an interface, the distance of a discontinuity from the pulse source, and the attenuation along the wave path. The influence of each of these factors is considered in the following discussion.

The portion of an incident plane compression wave that is reflected at an interface between two media of different densities or elastic moduli depends on the specific acoustic impedances of each medium. The specific acoustic impedance, Z, of a medium is

$$Z = \rho C_p \tag{10}$$

Since C_p is approximately equal to $\sqrt{E/\rho}$

$$Z \sim \sqrt{E \rho} \tag{11}$$

Specific acoustic impedance values for compression waves in selected materials are given in Table 2. Equation (10) is also valid for shear waves if the shear wave velocity, C_s, is used to calculate acoustic impedance.

The intensity of reflected energy, I_r, is maximum when the angle of incidence is normal to the interface and is determined from the following equation [4]:

$$I_r = I_i \left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2 \tag{12}$$

where I_i is the intensity of the incident energy. As shown by equation (2), the amplitude of the returning echo will be proportional to the square root of I_r. At an interface between a solid and a gas, such as between concrete and air, the specific acoustic impedance of the solid is so much larger than that of the gas that virtually all the incident energy is reflected producing a strong echo. For cases of oblique incidence the amplitude of the reflected waves will depend on the angle of incidence as well as on the acoustic impedance mismatch [2]. If mode conversion occurs, the reflected energy will be split between the different wave modes.

Coefficients of reflection for the amplitude of a reflected wave as a function of the angle of incidence can be determined using the formulas in Reference [2], which are applicable for plane waves incident upon plane boundaries. These formulas were used to calculate the reflection coefficients for a concrete/air interface. Figure 4 shows reflection coefficients for an incident P-wave, and Figure 5 shows reflection coefficients for an incident S-wave. It is assumed that each incident wave has an amplitude equal to unity. Each figure is composed of three graphs. The graph in the upper left gives the reflection coefficients for the wave with the same mode as the incident wave; for example, in Figure 4, which is for an incident P-wave, the upper left graph shows the reflection coefficients for a reflected P-wave. The graph in the lower right gives the reflection coefficients for the mode-converted wave. The lower right graph in Figure 4 shows the reflection coefficients for the S-wave produced by mode conversion of the incident P-wave. The graph in the upper right gives the angular relationship between the incident wave and the mode-converted wave, which is determined using Snell's Law. The drawing in the lower left gives an illustrative example. In Figure 4 the lower left drawing shows a P-wave (amplitude equal to unity) incident on a concrete/air interface at an angle of 30°. The angle of the reflected P-wave, θ_p, is equal to the angle of the incident P-wave; thus a horizontal line can be drawn from $\theta_p = 30°$ to the graph of the reflection coefficients for the reflected P-wave. In this case R_p is equal to 0.56, i.e., the amplitude of the reflected P-wave is 56% of the amplitude of the incident P-wave. If a second line is drawn horizontally from $\theta_p = 30°$ to the graph representing Snell's Law, the angle of the shear wave produced by mode conversion of the incident P-wave can be obtained ($\theta_s = 18°$). Subsequently, the reflection coefficient for the mode-converted shear wave, R_s, can be determined. In this example R_s is equal to 0.62, i.e., the shear wave has an amplitude equal to 62% of the incident P-wave.

In the previous discussion it was assumed that reflection and refraction of wave fronts occurred at planar interfaces between two dissimilar media. This analysis is also applicable to flaws or discontinuities within a medium. The ability of the pulse-echo method to detect flaws or discontinuities (sensitivity) depends on the wavelength of the propagating wave and on the size and orientation of the flaw or discontinuity. Waves will diffract or bend around the edges of discontinuities if the size of the discontinuity is approximately equal to or less than the wavelength; therefore, no reflection occurs for flaws that have lateral dimensions less than the wavelength. Figure 6 shows the relationship between frequency and wavelength for the range of compression wave velocities typically measured in concrete. To be able to detect flaws on the order of 0.1 meters it would be necessary to introduce into the concrete a stress pulse that contains frequencies greater than 20 kHz.

2.6 Diffraction at a Crack Tip

When a stress wave is incident upon a crack within a solid, the pattern of re-radiated energy is determined by four processes [10]:

1. Specular reflection from the crack face,
2. Rayleigh waves which travel along the crack surfaces and radiate energy when reaching the crack tips,
3. Diffracted spherical waves which originate from the crack tip, and
4. Mode conversion.

Specular reflection, produces the strongest echo signals and is the easiest to analyze; however, this reflection has a strong angular dependence and can only be detected if the crack is oriented at a favorable angle to the propagating wave and receiving transducer. If a crack is not oriented at a favorable angle for detection of specularly reflected waves, the signals received from diffracted waves can be used to detect the presence of cracks [11]. Figure 7a shows the specularly reflected wave front (PP) produced by a spherical P wave incident upon a crack [12]. Ray OA, which intersects the crack tip will be diffracted, producing an additional spherical wave

(P_d), as shown in Figure 7b. Note that diffraction permits the stress wave to penetrate the "shadow zone" behind the crack. (A similar situation would occur for an incident S wave.) Researchers have been able to record photographic images of diffraction using photoelasticity [13, 14], which confirm the conditions depicted in Figure 7b. The amplitude of particle motion in a diffracted wave varies with direction and, according to theoretical calculations, the amplitude in the diffracted wave is an order of magnitude less than the amplitude of specularly reflected waves [10].

2.7 Attenuation and Divergence

As a wave propagates through a solid the acoustic pressure (and thus the amplitude of particle motion) decreases with path length due to attenuation (scattering and absorption) and divergence.

In a heterogeneous solid, scattering is the result of wave reflection, refraction, diffraction, and mode conversion at each interface between dissimilar media. In ordinary concrete the density and the elastic modulus of the coarse aggregates are generally higher than those of the mortar; thus, from equation (11), the specific acoustic impedance of the coarse aggregate is higher than that of the mortar. If the wavelength of the propagating wave is less than the size of the aggregate, this mismatch in impedances causes scattering of the incident wave and returning echoes as the waves undergo reflection and refraction from each mortar-aggregate interface [7]. For higher quality[1] concrete the specific acoustic impedance of the mortar approaches that of the coarse aggregate and scattering is reduced. In pulse-echo evaluation of concrete lower frequency waves must be used (i.e., the wavelength-to-aggregate-size ratio must be increased [15]) to reduce the attenuation of wave energy due to scattering. However use of lower frequency waves reduces the sensitivity of the propagating wave to small flaws. Thus there is an inherent limitation in the flaw size that can be detected within concrete.

Although attenuation of wave energy in heterogeneous solids is primarily due to scattering, part of the wave energy is absorbed and turned into heat (hysteretic damping) [9]. In solids damping is mainly caused by internal friction.

Due to attenuation, the acoustic pressure of a plane wave decreases exponentially with path length and can be determined from the following equation [2]:

$$P = P_o e^{-\alpha d} \tag{13}$$

where P_o is the initial acoustic pressure, α is the attenuation coefficient [dB/m], and d is the length of the wave path [m]. Since scattering is the principle cause of attenuation, the value of α depends upon the wavelength of the propagating wave. Thus, the higher the frequency of the wave that is used to probe a given material, the larger will be the value of α for that material. The published data on α-values for concrete are scant.

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[1]Quality in this context refers to the density and elastic modulus of the mortar phase. Higher quality is synonymous with higher density and greater elastic modulus or both.

However, based on available information [16, 17], it appears that for frequencies on the order of 100 to 200 kHz, the probable range of values for α is 0.3 to 30 dB/m. Figure 8 shows the decrease of the acoustic pressure of a plane wave as a function of the length of the wave path for this range of α-values. It is seen that for the lower limit of α the loss of acoustic pressure with path length is small. However, for the upper limit of α there is a drastic decrease in acoustic pressure with path length. Thus, careful consideration must be given to the frequency content of the wave that is used to probe large concrete members.

In addition to causing a decrease in the acoustic pressure, attenuation also affects the frequency content of a pulse propagating in a heterogeneous medium [18]. Transmitted pulses contain a range of frequencies. In a material such as concrete the higher frequency components of the propagating pulse will be preferentially attenuated with path length. As a result, the frequency spectrum of the pulse is continuously shifted to lower frequencies. Thus, both the sensitivity and the acoustic pressure of a pulse decrease with path length.

For non-planar waves, reduction of the acoustic pressure also occurs due to spreading of the wave front as it propagates through the test medium (divergence) [8]. For the case of a point source producing a spherical wave front, divergence causes the acoustic pressure to vary as the inverse of the distance from the source [4]. For other types of sources, such as transducers, a "near-field" region exists close to the source within which the acoustic pressure varies in a complex manner. However, beyond the near-field[2], the acoustic pressure will decrease at a rate approximately equal to that experienced by a spherical wave [2].

The path of a received signal includes both the incident path (source to flaw) and the reflected path (flaw to receiver). Both incident and reflected waves undergo attenuation and divergence; thus, the amplitude of the echo signal will decrease dramatically with total path length. The relative losses caused by attenuation and divergence will depend upon the characteristics of both the test medium and the propagating wave [2]. For example, if high frequency (non-planar) waves are used to test a material with a low attenuation coefficient, such as a fine-grained steel (α = 1 to 3 dB/m for frequencies in the range of 2 MHz [2]), the decrease in acoustic pressure due to divergence of the acoustic beam in the far-field will limit the thickness of the object that can be probed. If the same high frequency waves are used to test a heterogeneous, porous material such as concrete (α > 100 dB/m for frequencies in the MHz range [2]), the proportion of losses caused by attenuation will predominate, severely limiting the penetrating power of the propagating wave.

[2]The end of the near-field (the beginning of the far-field) can be determined based on the size of the source and the frequency of the propagating wave [3].

3. INSTRUMENTATION

A typical pulse-echo testing system consists of three essential units: a pulse source, a receiving transducer, and a cathode-ray oscilloscope, as shown in Figure 1.

3.1 Pulse Source

Electro-acoustic transducers and mechanical impact are the two common methods used to introduce a stress pulse into a test object. The selection of a pulse source for a specific application depends upon the size of the flaws to be detected and on the characteristics of the test medium. In the inspection of metals, high-frequency, short-duration, pulses are introduced into a test object by an electro-acoustic transducer. The transducer is shock-excited by a short, high voltage pulse, which causes it to vibrate (ring) at its own resonant frequency for a few cycles and transmit a pulse into the test object [9]. No commercial transducers are satisfactory for pulse-echo testing of concrete, thus a mechanical impact source normally is used to generate a stress pulse with sufficient acoustic energy to overcome the effects of attenuation and divergence. The type of mechanical impact source that is used will determine the energy and the frequency content of the pulse. The force-time function of the impact can be approximated as a half-sine curve. The amplitude of the force-time function will affect the amplitude of particle motion (and thus the acoustic pressure) as the pulse travels through the test object, and the contact time of the force-time function will affect the frequency content of the pulse. The notion of frequency content arises from the principle of Fourier series, whereby the pulse shape can be approximated by the sum of a number of sine functions of different frequencies. Many sine curves are required to approximate the pulse shape produced by a short contact time, and thus the input energy is distributed over a wider frequency range. This frequency range will control the minimum flaw size that will be capable of reflecting the pulse: the higher the frequency range, the smaller is the flaw that will reflect acoustic energy.

3.2 Transducer

The transducer is the critical element in any testing system based on acoustic wave transmission and reception. Transducer response must be accurate and reliable. Ideally a transducer should respond faithfully to only one physical parameter (e.g., the normal component of surface displacement or velocity) so that the response can be correctly interpreted. However, conventional transducers usually do not measure a single parameter because of the effects of the coupling between transducer and test object, the electronics, and the characteristics of the transducer itself [19].

The majority of electro-acoustic transducers used in high-frequency pulse-echo systems utilize piezoelectric crystals in the generation and reception of stress waves. A piezoelectric material is one which generates an electrical charge when subjected to a mechanical stress or deformation. Single crystals of many compounds exhibit piezoelectricity. Traditionally natural crystals, such as Rochelle salt and quartz, were used in the construction of crystal transducers. Although still used in specific applications, natural crystals have been almost completely replaced by manufactured ceramic materials.

If the elastic limit of the piezoelectric material is not exceeded, the charge densities produced by the piezoelectric effect are directly proportional to the strain of the crystal. Conversely, a piezoelectric crystal subjected to an electrical charge will produce mechanical deformation (vibration) [20]. Thus, a single piezoelectric transducer can be used for both generation and reception of stress waves in pulse-echo systems. However, when a single transducer is used, transmitted pulses must be of short duration, otherwise the ringing of the transducer crystal will render it insensitive to echoes returning from flaws or interfaces. In addition a transducer must have the capability to separate echoes which are close together (resolution). If a second signal arrives while a crystal is still vibrating due to an earlier excitation, the second signal will either be mixed in with the first signal making the signal record difficult to interpret or it will go unnoticed, depending on the relative strength of the echo signals [8]. Thus, a crystal is "blind" for a short time after each excitation. To prevent ringing and to reduce blind-time a transducer must be heavily damped [9]. However, damping decreases a transducer's sensitivity [8]. The more a transducer is damped, the stronger must be the returning echo that will cause it to vibrate. Small flaws may not reflect sufficient energy to excite the transducer and no signal will be produced on the oscilloscope screen. Thus, an acceptable balance between resolution and sensitivity must be achieved in the design and construction of a piezoelectric transducer.

The ratio of the transducer diameter, d, to the wavelength of the transmitted waves, λ, determines the shape of the acoustic beam. Figure 9 [2, 21] shows the directional characteristics for $d << \lambda$, $d/\lambda = 1$, and for $d/\lambda = 4$. Most of the energy in an acoustic beam is contained within a cone-shaped region which has its apex at the transducer. As d/λ decreases the apex angle of the cone increases, i.e., the directionality of the acoustic beam becomes less pronounced. A transducer's "field-of-view" is determined by its directional characteristics, and it is this field-of-view that will determine the interrogation pattern that is required to fully probe the interior of a test object. Increasing d/λ reduces the field-of-view by focusing most of the acoustic energy into a narrow compression wave beam. A transducer that emits a focused beam (Figure 9a) can be used much more effectively to probe a test object as it allows flaws or interfaces to be located more precisely.

3.3 Oscilloscope

The introduction of the pulse into the test object triggers the oscilloscope's time base circuit, which provides a linear traverse of the cathode-ray beam from left to right across the screen. The transmitted pulse and returning echoes are displayed as vertical offsets from the horizontal traverse (see Figure 1b). (In multi-channel oscilloscopes transmitted pulses and returning echoes can be displayed on separate traces.) Using the time base on the display, the time from the start of the pulse to echo arrival can be determined. In research applications a digital storage oscilloscope is preferred to enable detailed analyses of the received signals.

3.4 Pulse-echo Signal Traces

As an illustration of the pulse-echo technique for concrete, selected echo signals are shown in Figures 10a and 11. These signals were obtained by using a transducer recently developed at the National Bureau of Standards which accurately measures normal surface displacement [22]. Figure 10a is a plot of a portion of a signal recorded by a digital oscilloscope during a test on a 0.25-m thick, 1.12- by 1.12-m concrete slab. The receiver was located at the slab center on the top surface. The stress pulse was generated by dropping a 8-mm steel ball onto the slab from a height of 0.19 m. The separation between the impact point and receiver was 0.125 m. In this case it can be assumed that the impact of the steel ball acts as a point source emitting a pulse of acoustic energy into the slab in all directions. Figure 10a also indicates the theoretical arrival times of various acoustic rays which were calculated based on a measured compression wave velocity of 3980 m/s and an assumed Poisson's ratio of 0.2. The paths of selected acoustic rays are illustrated in Figure 10b. The first rays to arrive are the direct P, S, and R-waves, which travel along the top slab surface. The signal due to the arrival of the R-wave is very strong; thus, clear identification of the arrival of the PP-ray (a reflected compression wave due to a compression wave incident on the bottom slab surface) is not possible in this signal record. Mode conversion of a compression wave incident upon the bottom slab surface results in a reflected shear wave (PS) which arrives after the PP-ray since the velocity of a shear wave is only 61 percent of the velocity of the compression wave. The subsequent peaks in Figure 10a are due to the reception of multiply reflected compression waves. There is excellent agreement between the signal maxima and the computed arrival times of the 4P and 6P-rays.

Figure11 is a plot of a portion of a recorded signal obtained from a test on a 0.5-m thick concrete slab containing a disc-shaped void (0.5 m in diameter) located 0.25 m below the top slab surface. In this test the separation between the impact point and the receiver was 0.10 m. Notice the similarities between this figure and Figure 10a. The theoretical arrival times of reflected rays were calculated based on reflections from the concrete/void interface, a measured compression wave velocity of 3900 m/s, and an assumed Poisson's ratio of 0.2. The agreement between the signal maxima and the computed arrival times clearly indicates that the rays are being reflected by the concrete/void interface. The 0.10-m separation between source and receiver (0.025 m less than in the previous case) provides a greater time lapse between the arrival of the R-wave and the arrival of the PP-ray. Since the disturbance due to the R-wave has time to decay before the arrival of the PP-ray, the PP-ray is easily identified in Figure 11.

Although the traditional approach in pulse-echo testing has been to study the signal record in the time domain, the Fast Fourier Transform technique can be used to obtain the frequency content of a time domain digital signal record [2]. The frequency spectrum of a received signal can be used to determine thicknesses of plate elements or to estimate the size and location of flaws, a spectrum analyzer is employed to transform the time domain trace of the recorded signal into a frequency domain plot. Figure 12 is a plot of the frequency spectrum corresponding to the time domain signal record shown in Figure 10a. The peak frequency, 7.81 KHz, can be used to estimate the slab thickness. In this example the peak frequency predicts a slab thickness of 0.255 m which agrees well with the actual thickness of 0.25 m.

4. PAST RESEARCH

The use of acoustic waves for the detection of flaws in solids dates back to 1929, when Sokolov of Russia first suggested the use of ultrasonic waves to find defects in metal objects [9]. Development of practical nondestructive test methods was slow; it was not until the nearly simultaneous introduction of pulse-echo flaw detectors in 1942 by Firestone of the University of Michigan and by Sproule of England that significant progress was made. Since that time ultrasonic pulse-echo testing of metals, plastics, and other homogeneous materials has developed into an efficient, reliable, and versatile nondestructive test method. The extension of acoustic pulse-echo principles to less ideal materials, such as concrete, has been hindered by the difficulties inherent in obtaining and interpreting a signal record from a heterogeneous material, although some progress has been made in developing systems for measuring the thickness of plate elements and for integrity testing of rod-like structures such as piles.

4.1 Pavements and Bridge Decks

Resonance and pulse-echo techniques have been used to measure the thickness of concrete pavements and to detect delaminations in bridge decks. In the early 1960's, Muenow [23] developed a technique to measure pavement thickness that was based on determining the frequency of the fundamental mode of vibration of the slab in the thickness dimension. Continuous compression waves were introduced into the slab by a transmitter. The frequency of these waves was systematically varied until a resonance condition[3] was obtained. Slab response was monitored by a receiving transducer which was located adjacent to the transmitter. Transmitted and received signals were displayed separately on a two channel oscilloscope. The fundamental mode of longitudinal resonance was identified by noting the frequency, f, at which a marked increase in the amplitude of the received signal occurred and by measuring the phase angle between the transmitted and received signals. If the P-wave velocity in the slab is known, the thickness of the slab, t, which equals one-half the wavelength of the propagating wave, could be calculated ($t = \lambda/2 = C/2f$).

Resonance methods have also been used to detect delaminations in concrete bridge decks. A technique developed in 1973 by researchers at Texas A & M University [24] used an oscillating steel plunger to excite the characteristic vibrations of a delaminated area. As the plunger oscillates at 60 Hz, the vibrations of the bridge deck were monitored by a receiving transducer. The location and extent of delaminated areas could be determined from the relative amplitude of the received signal. The use of this technique has been limited by the fact that it cannot be used where concrete decks have asphaltic overlays exceeding approximately five cm.

[3]A resonance condition is produced when standing waves are set up, that is, when waves are repeatedly reflected within a medium in such a way that their wavelengths are superimposed exactly in phase [9].

In 1964, Bradfield and Gatfield [25] of England reported the development of a pulse-echo technique for measuring the thickness of concrete pavements. Using two 100 kHz resonant transducers (16 cm tall, 10 cm wide, and 25 cm long) they were able to measure the thickness of a 12-inch concrete specimen with an accuracy of approximately 2%. However this system could not be field tested [24] due to the impracticality of the test set-up. Besides being bulky, the transducers were coupled to the concrete by a large plastic block which required a large smooth flat concrete surface for good coupling. Difficulties were also reported in obtaining reflections from rough textured bottom pavement surfaces.

In 1968, Howkins, et al, at IIT Research Institute [26] independently investigated available resonance and pulse-echo techniques in an attempt to identify a feasible method for pavement thickness measurements. Tests using the resonance technique proposed by Muenow [23] and the pulse-echo technique proposed by Bradfield and Gatfield [25] were performed. Although it was felt that the resonance technique was, in principle, a good approach, significant reservations were stated concerning the reliability of Muenow's resonance method. Using a pulse-echo technique similar to that developed by Bradfield and Gatfield, the IIT researchers were able to measure the thicknesses of 7 and 10-in thick portland cement concrete slab specimens, for simple support conditions and for slabs supported on a 4-in thick gravel base course, and a 5-in thick, simply supported bituminous concrete slab specimen with an accuracy of $\pm$ 2%. However, it was concluded that the transducer arrangement was not practical for field use.

A pulse-echo system was developed at Ohio State University in the late 1960's [27] to measure pavement thickness by monitoring the travel time for an ultrasonic pulse to propagate through the thickness of the concrete and return to the receiving transducer at the top surface after being reflected by the concrete pavement-subbase interface. A large transmitter was needed to introduce sufficient acoustic energy into the test medium to overcome wave attenuation problems due to coarse-grained aggregates and to obtain coherent reflections from rough pavement-subbase interfaces. The transmitter was circular in design, with a 46 cm outer diameter, a 15 cm inner diameter, and a 200 kHz resonant frequency. The receiving transducer was placed in the center of the transmitter. Accuracies of plus or minus 3% at more than 90% of the test locations were obtained. The accuracy and good performance of the Ohio State thickness gage was confirmed in independent field tests conducted in 1976 by Weber, Gray and Cady [28]. However, Weber, et al concluded that the Ohio State instrument will have to be redesigned to better withstand the rigors of field use before it can be considered as a practical nondestructive method.

4.2 Dams

Engineers in India [29] used a sonic pulse-echo method to estimate the depth and extent of large horizontal cracks that developed in the Koyna dam during a major earthquake in 1967. Very low frequency acoustic waves (200-600 Hz) were introduced into the concrete by mechanical impact with a free falling steel hammer. This range of sonic frequencies allowed detection of cracks on the order of 15 m and larger. The energy generated by the mechanical impact was sufficient to obtain reflections from cracks located 100 m away from the point of impact. After existing cracks were grouted the pulse-echo technique was used to assess the degree of grout penetration. The assessment was made qualitatively by comparing the echo amplitudes in signal records obtained before grouting to those obtained after grouting.

4.3 Piles

Since the early 1970's pulse-echo principles have been widely used for integrity testing of concrete piles [7, 30-39]. The behavior of stress waves in slender, rod-like structures, such as piles, is well known. If a pulse is generated by mechanical impact at one end of a rod, the resulting wave front is initially spherical but quickly becomes planar as the pulse propagates down the long slender rod. Plane wave reflection occurs at the bottom surface, and the reflected wave front travels back up the length of the rod to be picked up by the receiving transducer. Thus the rod acts as a "waveguide." As a result, echo signal analysis is relatively uncomplicated. Steinbach and Vey [7] were among the first to apply pulse-echo techniques to field evaluation of piles. A compression pulse was introduced into a concrete pile at the top surface by mechanical impact and returning echoes were monitored by an accelerometer mounted on the same surface. The signal record could then be used to detect partial or complete discontinuities, such as voids, abrupt changes in cross section, very weak concrete, and soil intrusions, as well as the approximate location where such irregularities existed. In the absence of major imperfections the location of the bottom of a sound pile could be determined. However, little specific information could be obtained as to the extent of defects or the relative soundness of concrete at the location of an irregularity. The success of the method is dependent upon the damping characteristics of surrounding soil; a high degree of damping can severely weaken returning echoes.

4.4 Reactor Structures

In 1976 Sutherland and Kent [15] of Sandia Laboratories used the ultrasonic pulse-echo method to study the safety of concrete reactor substructures subjected to the thermal energy of a hypothetical core meltdown. The relative position of a concrete-gas interface subjected to a high heat flux from a plasma jet was monitored as a function of time to determine the erosion rate of the concrete substructure. Erosion rates were determined successfully for plain structural concretes with aggregate size variations from 3 to 75 mm.

4.5 Refractory Concrete

Claytor and Ellingson [16] used the pulse-echo method to measure the thickness of 30.5 cm thick refractory concrete specimens. It was found that for frequencies below 100 kHz the use of a single transducer as both the transmitter and receiver was impractical because the ringing of the transducer obscured the echo signal. When two transducers were used in a transmitter-receiver mode, ringing was not a problem; however, the transmitting transducer generated strong Rayleigh waves which interfere with the reception of the echo signal by the receiving transducer. To reduce interference due to Rayleigh waves large-diameter (17.8 cm) transducers were constructed. As the response of a transducer is an averaged phenomenon over the contact area, the sensitivity of a larger diameter transducer to localized surface disturbances (Rayleigh waves) will be reduced. To further reduce interferences due to Rayleigh waves a glycerin buffer was used between the transducers and the concrete specimens. The compression waves produced by mode conversion of the propagating Rayleigh waves radiate into the glycerin at an angle of 36°. Thus, the echo signal, which is incident on the glycerin at a much steeper angle (depending on the spacing of the transducers and on the orientation of the reflecting surface) is received with greater efficiency.

4.6 Submerged Structures

Smith[4] demonstrated that Rayleigh waves can be used to detect surface opening cracks in submerged concrete structures, such as concrete tanks and offshore structures. Two 0.5 MHz, 25-mm diameter, compression wave transducers were used as transmitter and receiver. When a transmitted compression wave strikes the surface of a solid at a critical angle (defined by Snell's Law) mode conversion occurs producing a Rayleigh wave which propagates along the solid-liquid interface. As the Rayleigh wave propagates, mode conversion also occurs, producing a compression wave which radiates into the liquid at the same critical angle and is picked up by the receiving transducer. The distance between the two transducers could be adjusted to optimize the amplitude of the received signal. If the path of the propagating Rayleigh wave is crossed by a crack, reflection occurs and no signal will be picked up by the receiving transducer. If a crack is favorably oriented (a crack at 90° to the propagating wave is the best orientation) the compression waves produced by mode conversion of the reflected Rayleigh wave will be picked up by the transmitting transducer. Analysis of the received signals obtained from a complete scan, i.e., from moving the transducers parallel to and over the surface of the test object in a prearranged pattern, allowed the location of surface opening cracks to be determined.

5. RESEARCH NEEDS

A review of the literature has shown that pulse-echo techniques have been used successfully to detect flaws within concrete. In particular, pulse-echo principles have been widely used for integrity testing of concrete piles. The technique and the instrumentation for the evaluation of this type of structures are fairly well established. Although limited success has been achieved in other specialized applications, no standardized method currently exists for general nondestructive evaluation of concrete structures. Based on the current state of knowledge, the following research areas need to be investigated if an efficient and reliable system for flaw detection in concrete is to be developed:

1. If the pulse-echo technique is to gain widespread acceptance, it will be necessary to standardize the key elements of the method. Standard elements of a pulse-echo system should include a reproducible input pulse with a well defined frequency content, instrumentation for accurate and reliable reception and display of reflected signals, and analysis techniques for efficient interpretation of the signal record.

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[4] Smith, R. L., "The Use of Surface Scanning Waves to Detect Surface Opening Cracks in Concrete," to be presented at Int. Conf. on In Situ/NDT Testing of Concrete, Oct. 2-5, 1984, Ottawa, Canada.

2. The characterization of flaws by frequency spectrum analysis (spectroscopy) should be investigated. Using the frequency distribution information may be obtained about the size, location, and orientation of internal defects. (The reader is referred to reference [40] which contains an introduction to the method and an extensive abstracted bibliography.)

3. A better understanding of elastic wave propagation in heterogeneous solids is essential. An analytical model is needed to describe the scattering of elastic waves by flaws and discontinuities. (For a review of proposed scattering theories the reader is referred to Ref. [41].) A numerical model based on a technique such as finite element analysis also should be considered, perhaps as an alternative to an analytical model. Such a model, after experimental verification, will enable parametric studies to evaluate the significance of the variables which affect the interaction between stress waves and flaws.

4. As has been discussed, the basic approach in acoustic nondestructive evaluation methods is to monitor the response of a test object under the stimulus of a pulse source with known input characteristics. Changes in the elastic properties and integrity of the object will be manifested as changes in the received signal. Mathematically, the response, h(x), of a medium to a given stimulus can be evaluated as the convolution[5] of the impulse response function (transfer function), g(x), of the medium with the stimulus (source function), f(x). The transfer function of the medium is a function of its elastic and geometric properties. Alternately, by the process of deconvolution, the transfer function may be obtained from the known stimulus and the measured response. Research is needed to evaluate the effect that changes in the physical characteristics of heterogeneous and porous solids have on the transfer function. The response of test objects, such as finite plates containing internal cracks and voids, to well-defined input functions needs to be measured experimentally so that transfer functions can be determined. By observing changes in transfer functions with systematic changes in the medium, techniques can be developed that will allow one to infer changes in the characteristics of the medium from changes in the transfer function.

If the difficulties inherent in obtaining and interpreting a signal record from concrete can be overcome, the pulse-echo method will provide a versatile, economical, and safe technique for the detection of flaws within concrete structures. It is further anticipated that the development of a standardized pulse-echo technique will lead to research in the area of acoustic imaging (holography). Holographic techniques may eventually make it possible to obtain a three-dimensional view of the internal structure of reinforced concrete elements.

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[5]The convolution of two functions f(x) and g(x) is also a function of x, say h(x), and is given by the following formula:

$$h(x) = \int_{-\infty}^{\infty} f(u)\, g(x-u)\, du = f(x) * g(x)$$

where * denotes convolution. If g(x) and h(x) are known, the process of determining f(x) is called deconvolution, and f(x) is called the inverse function. (The reader is referred to Reference [42] for a complete explanation of convolution and deconvolution.)

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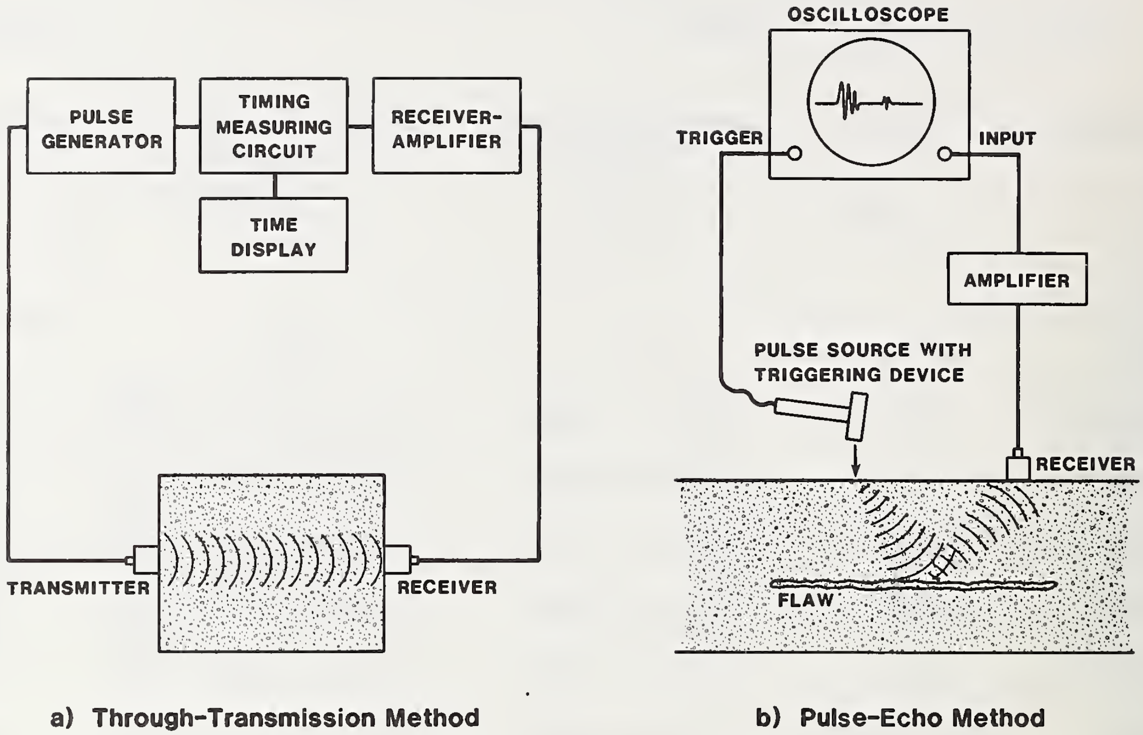
TABLE 1. Parameters of Acoustic Waves

Quantity	Symbol	Units
Mass Density of Material	ρ	kg/m^3
Acoustic Wave Velocity	C	m/s
Wavelength	λ	m
Frequency	f	1/s or Hz
Angular Frequency ($2\pi f$)	ω	rad/s
Amplitude of Particle Motion	A	m
Particle Velocity	v	m/s
Acoustic Pressure	P	N/m^2
Acoustic Intensity	I	W/m^2

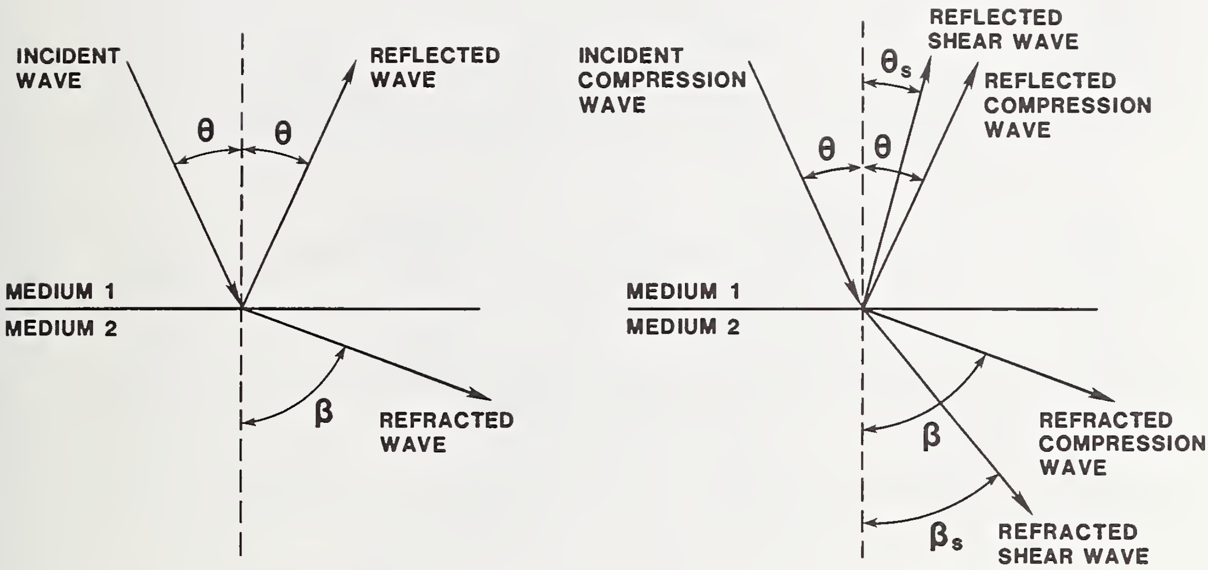
TABLE 2. Specific Acoustic Impedances

Material	Density ρ (kg/m^3)	Compression Wave Velocity C_p (m/s)	Specific Acoustic Impedance Z (kg/(m^2-s))	Reference
Air	1.205	343	0.413	43
Concrete[6]	2300	3000 to 4500	6.9 to 10.4 $\times 10^6$	--
Granite	2750	5500 to 6100	15.1 to 16.8 $\times 10^6$	44
Limestone	2690	2800 to 7000	7.5 to 18.8 $\times 10^6$	44
Marble	2650	3700 to 6900	9.8 to 18.3 $\times 10^6$	44
Quartzite	2620	5600 to 6100	14.7 to 16.0 $\times 10^6$	44
Soils	1400 to 2150	200 to 2000	0.28 to 4.3 $\times 10^6$	45
Structural steel	7850	5940	46.6 $\times 10^6$	2
Water	1000	1480	1.48 $\times 10^6$	2

[6]The mass density of concrete depends on the mix proportions and the specific gravities of the mix ingredients. The given density is for an average, normalweight concrete.



1. Schematic illustration of two acoustic nondestructive test methods: a) the through-transmission method; and b) the pulse-echo method.



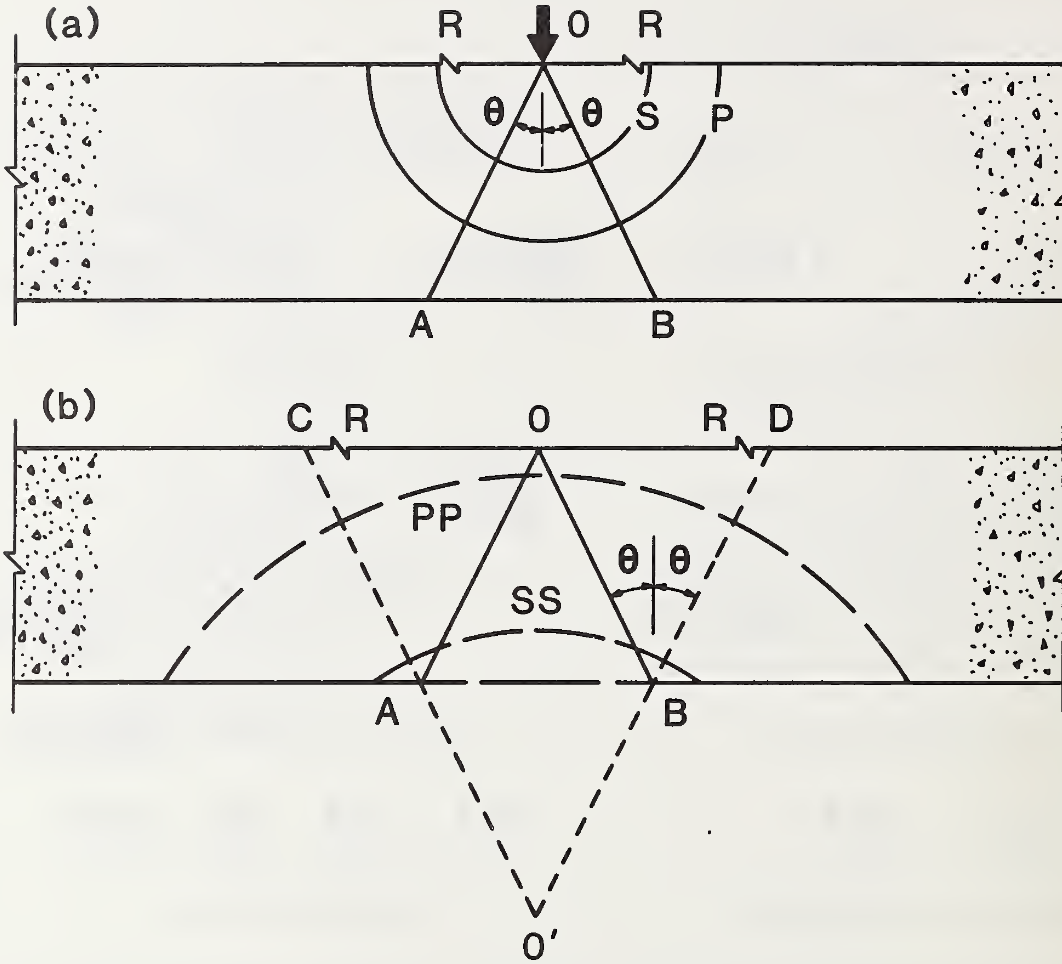
$$\frac{\sin\theta}{C_1} = \frac{\sin\beta}{C_2}$$

a) Reflection and Refraction

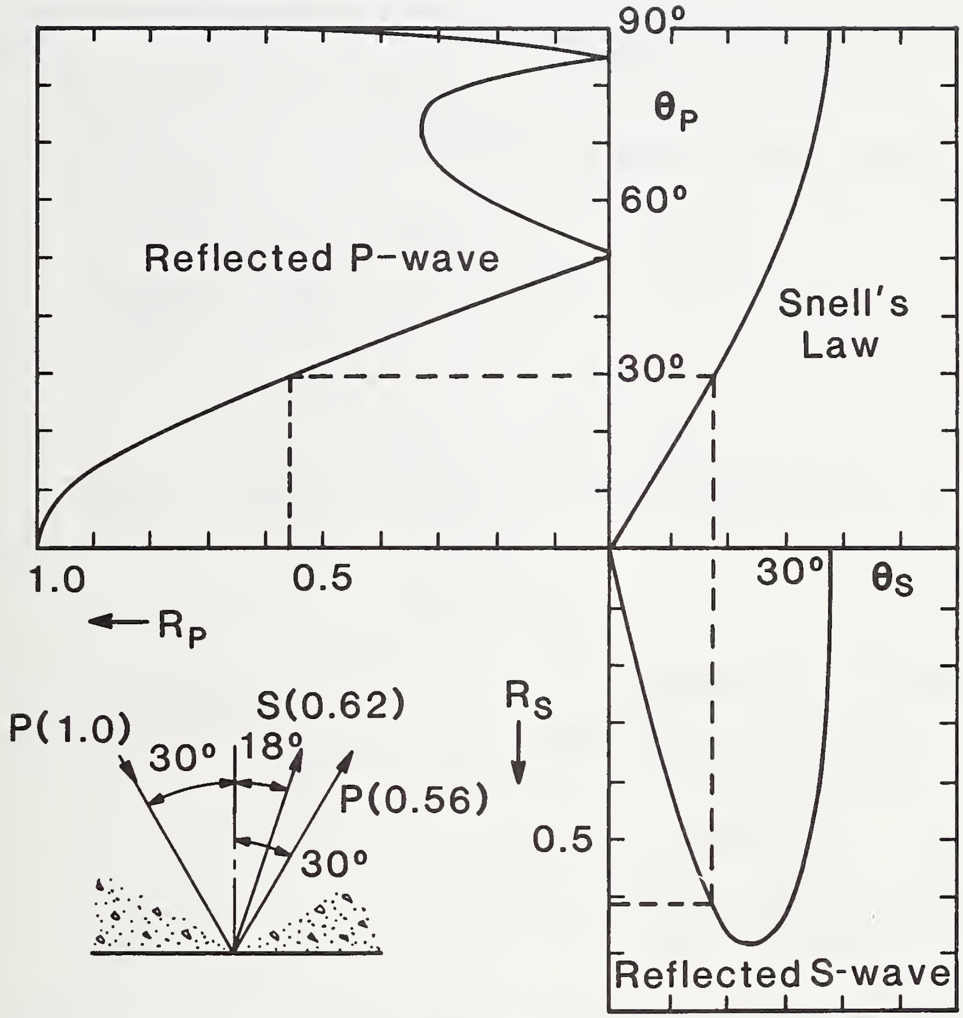
$$\frac{\sin\theta}{C_{p1}} = \frac{\sin\beta}{C_{p2}} = \frac{\sin\theta_s}{C_{s1}} = \frac{\sin\beta_s}{C_{s2}}$$

b) Mode Conversion

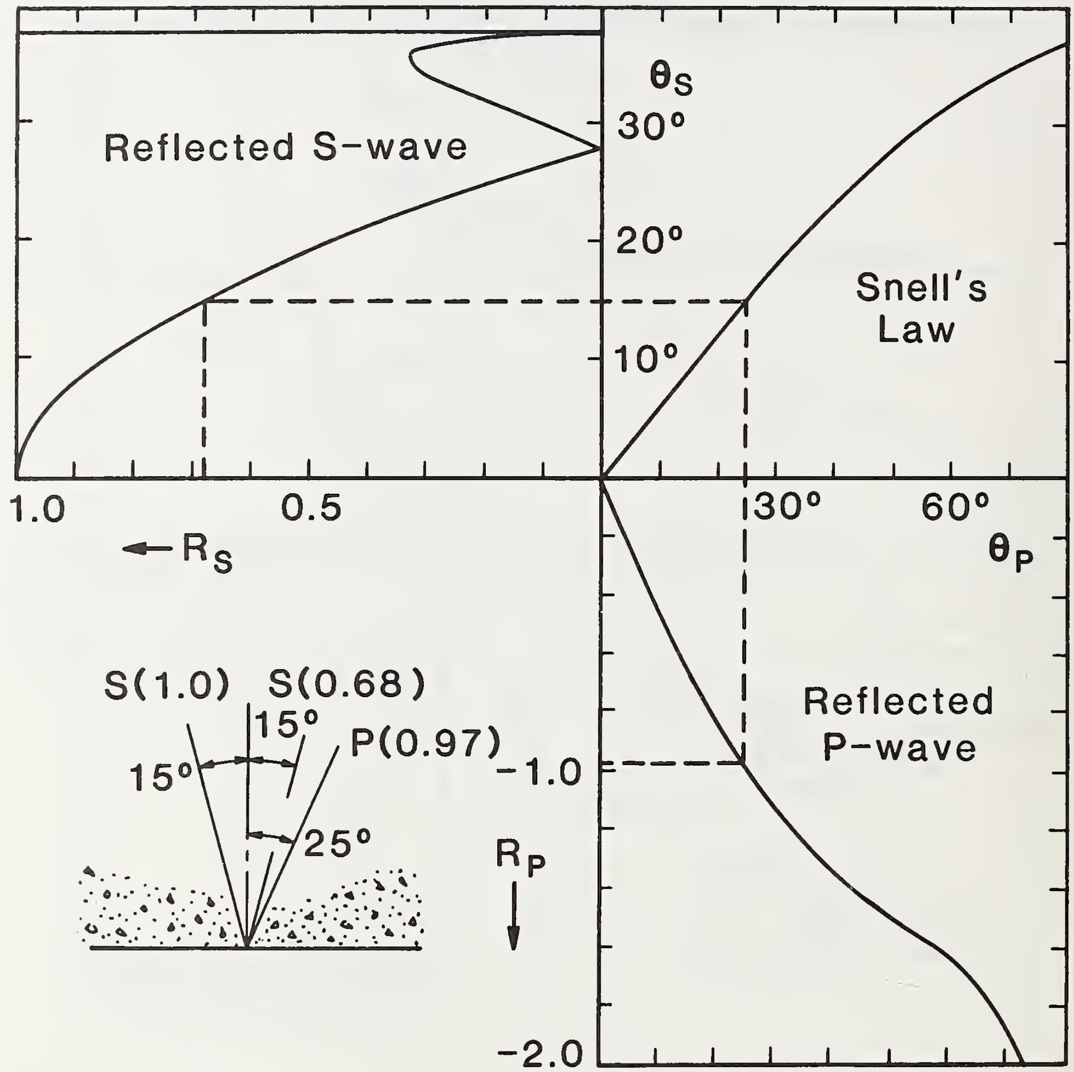
2. a) Spherical wave fronts due to impact on the top surface of a plate; and b) wave fronts after reflection from the bottom surface.



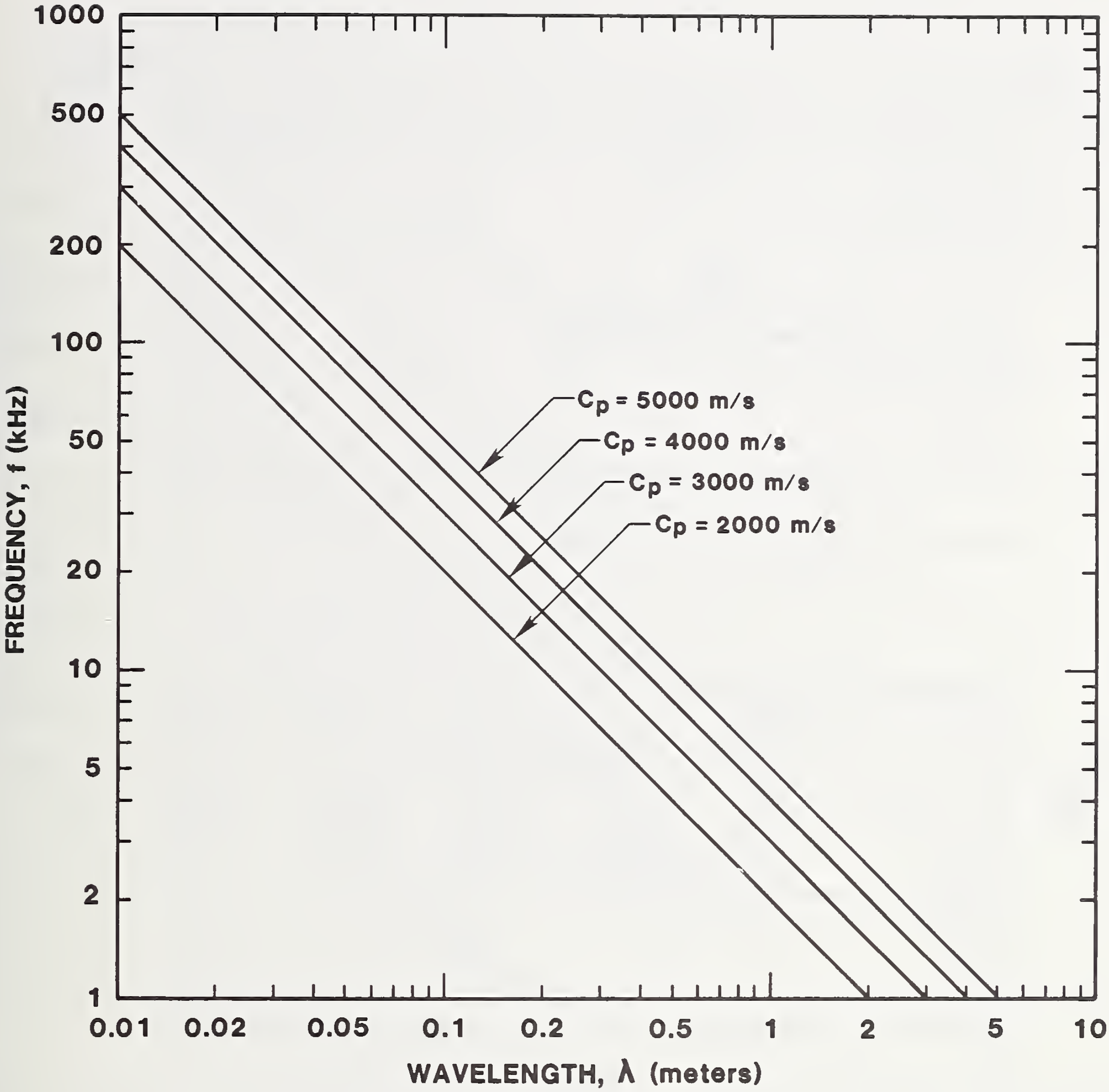
3. The behavior of a compression wave incident upon an interface between two dissimilar media; a) reflection and refraction; and b) mode conversion.



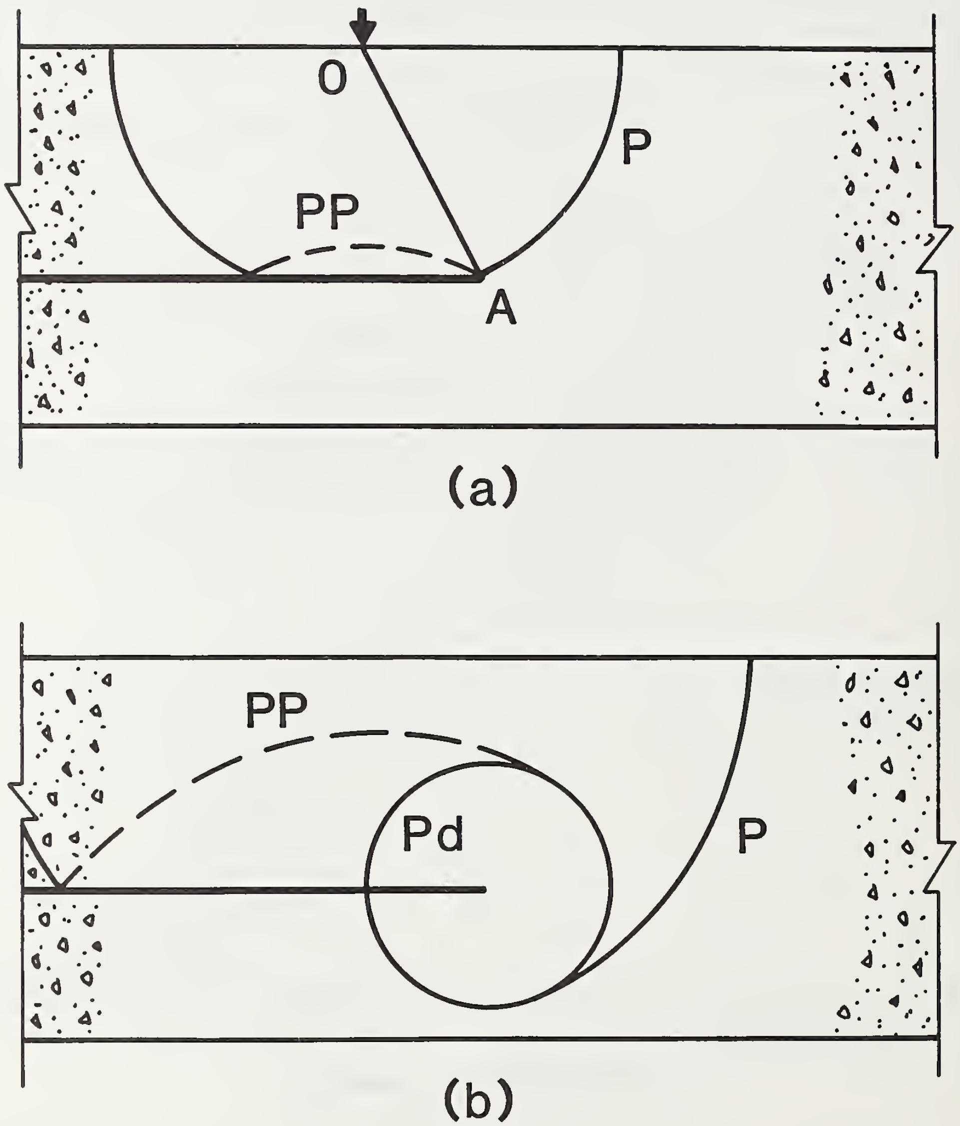
4. Reflection coefficients at a concrete/air interface for an incident P wave as a function of the incidence angle (Poisson's ratio = 0.2).



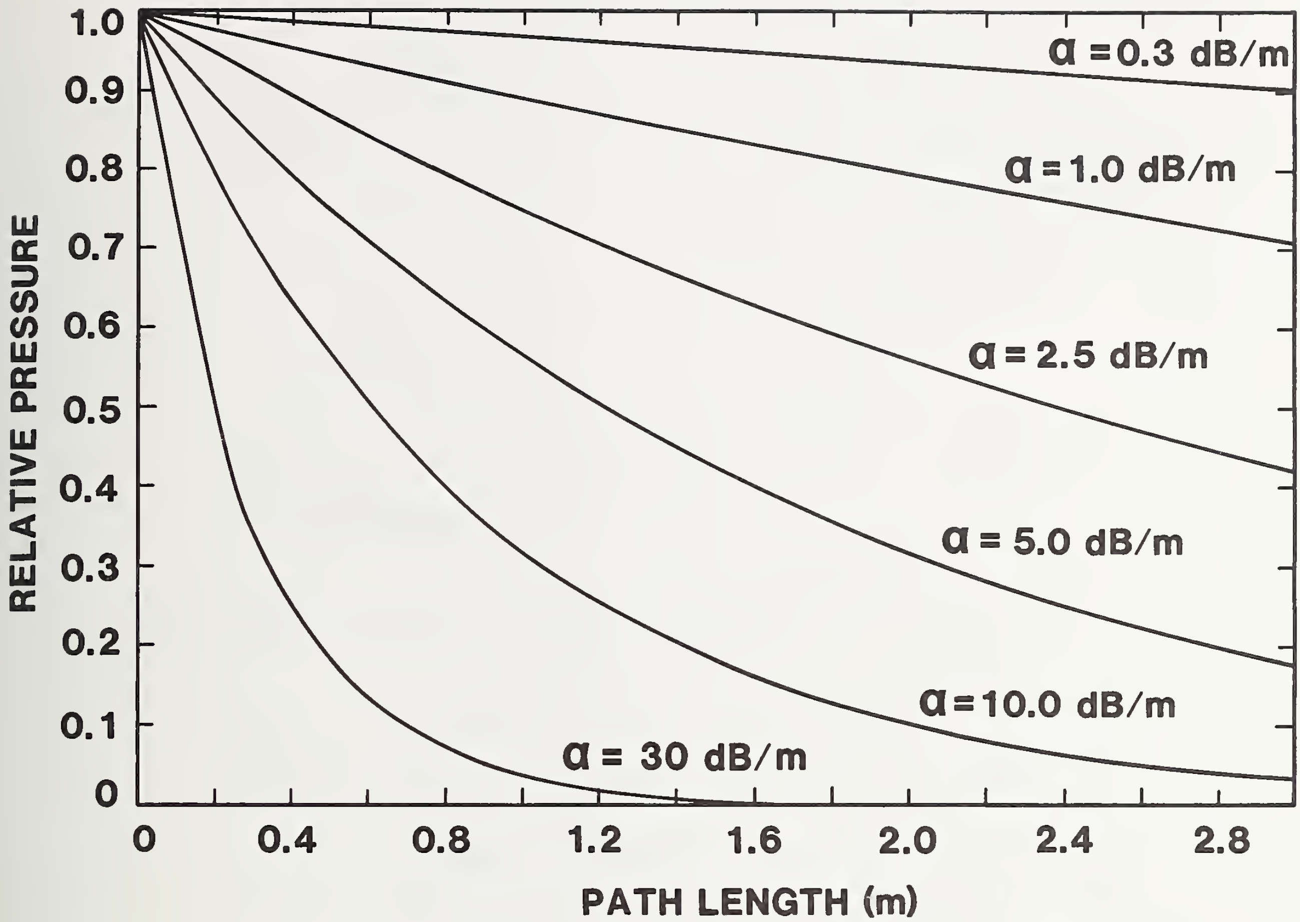
5. Reflection coefficients at a concrete/air interface for an incident S wave as a function of the incidence angle (Poisson's ratio = 0.2).



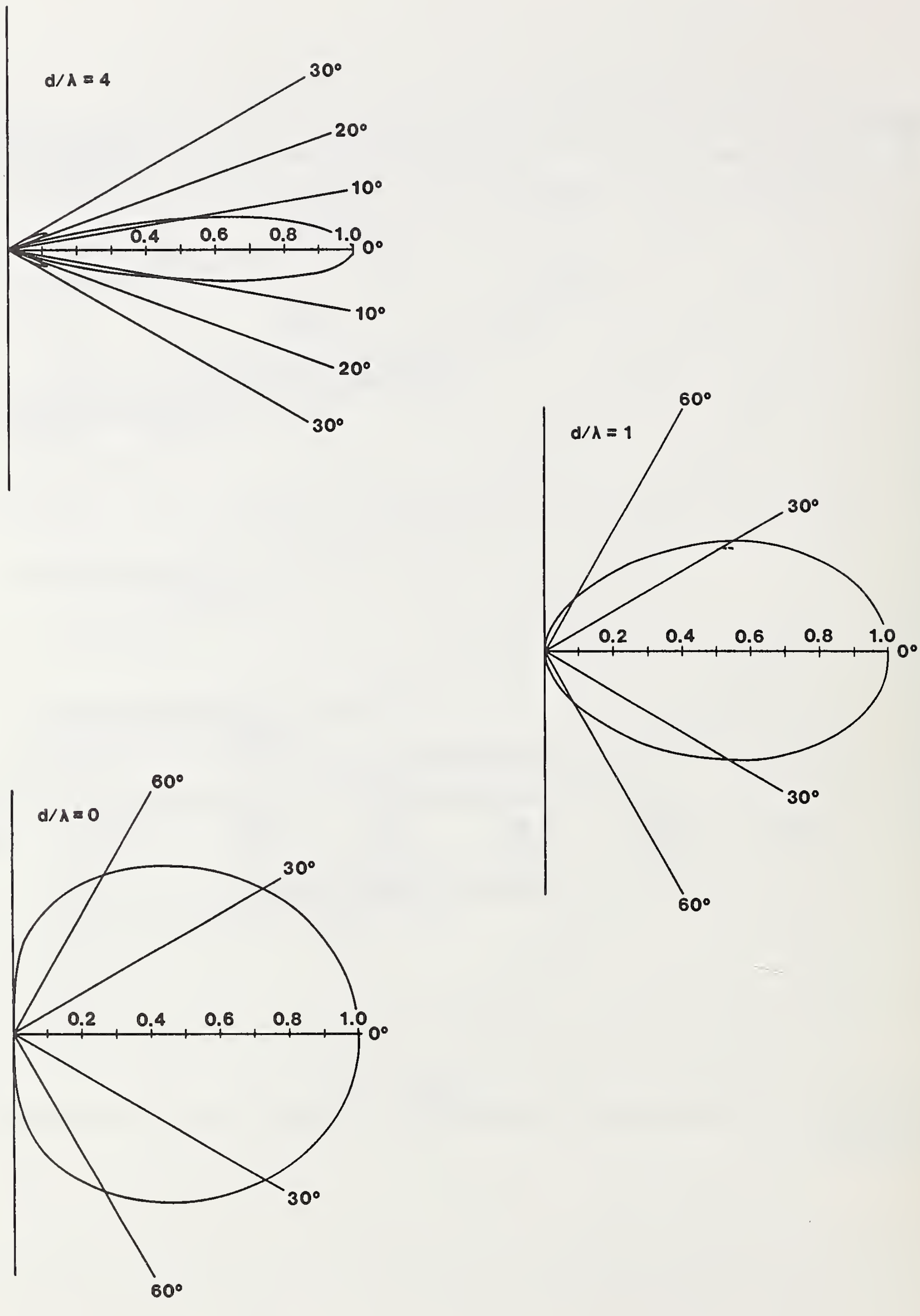
6. Relationship between frequency and wavelength for the range of compression wave velocities typically measured in concrete.



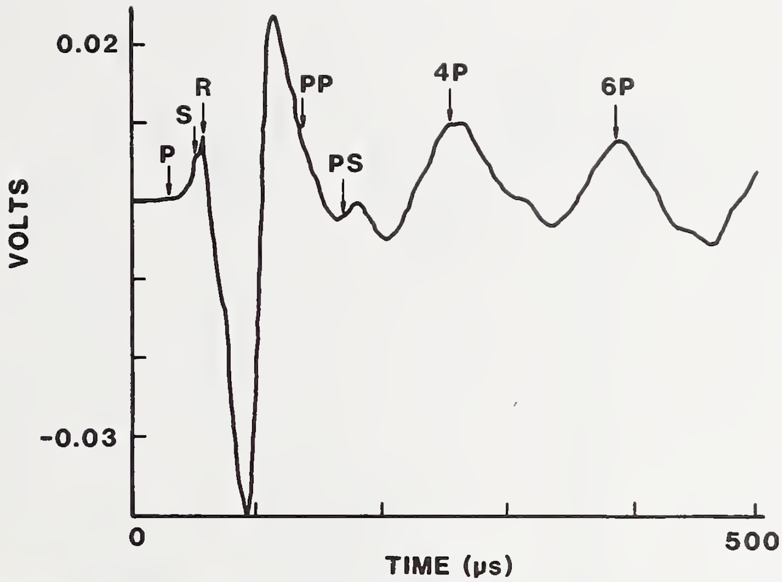
7. Diffraction effects due to a sharp edge: a) incident ray OA reaches the edge; and b) spherical wave front (Pd) emitted from the edge.



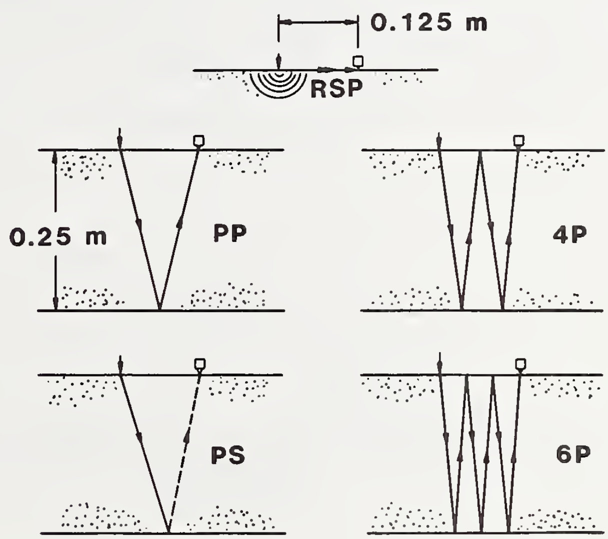
8. Attenuation of plane waves in concrete for frequencies in the range of 100 to 200 kHz.



9. Directional characteristics of transducers with various ratios of diameter to wavelength; a) $d/\lambda = 4$; b) $d/\lambda = 1$; and c) $d << \lambda$; (Poisson's ratio = 0.2).

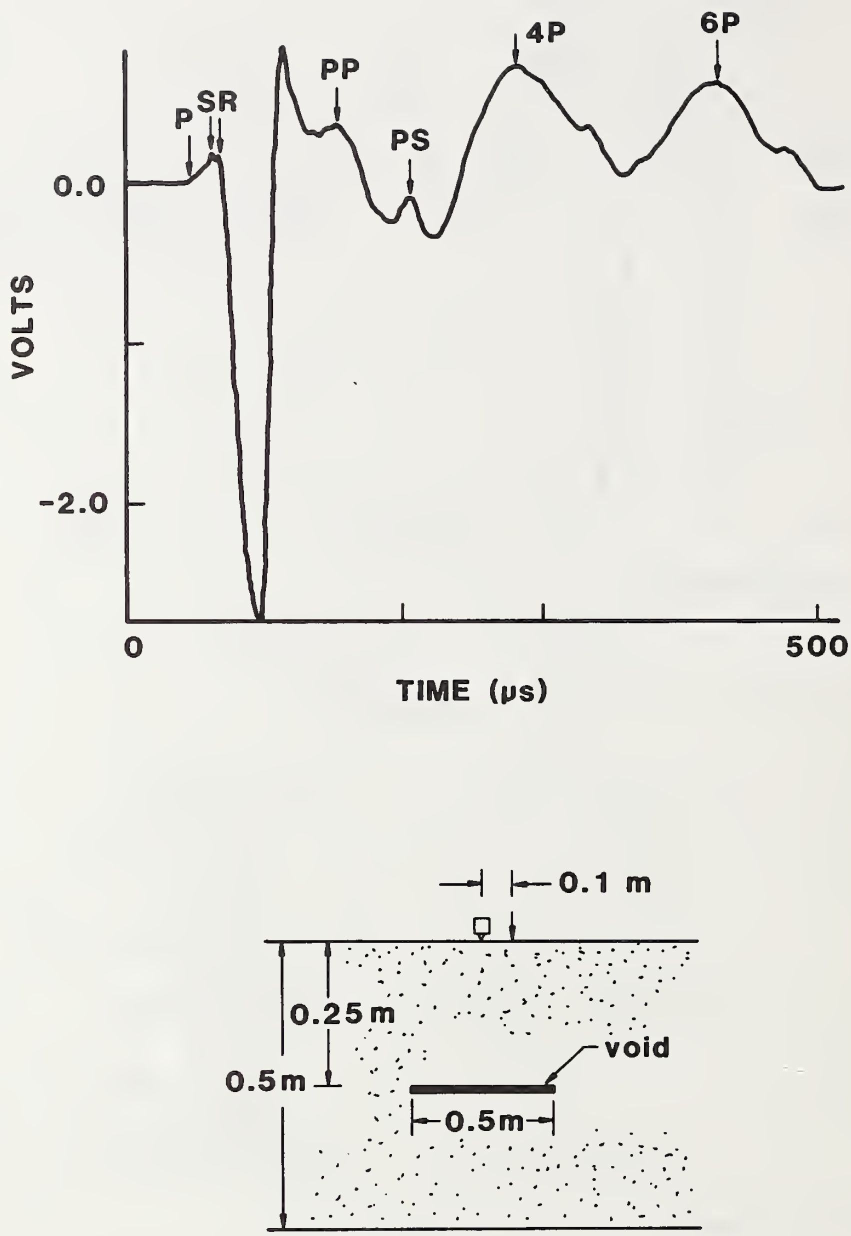


a) Oscillogram

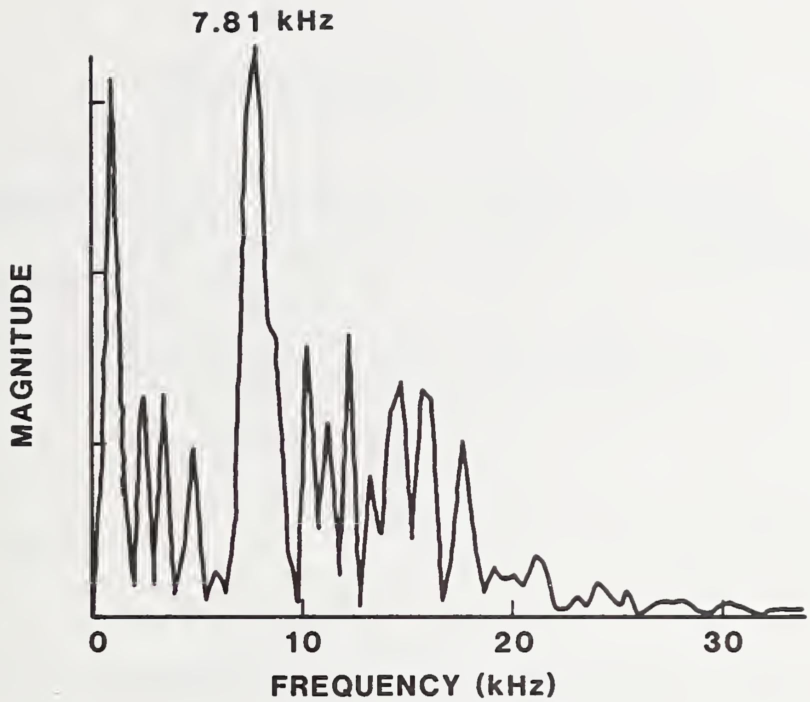


b) Ray paths

10. Pulse-echo results due to impact of a steel ball on the top surface of a 0.25-m thick concrete slab; a) oscillogram; and b) ray paths.



11. Oscillogram obtained during a test on a 0.5-m thick concrete slab containing a disc-shaped void 0.25 m below the surface.



12. Frequency spectrum from the transformation of the time domain signal shown in Figure 10a.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The basic principles of the pulse-echo method for the detection of internal flaws in concrete are presented. As the heterogeneous nature of concrete poses problems not encountered in pulse-echo evaluation of metals, progress in this area of concrete nondestructive testing has been slow. A review of past research shows that pulse-echo techniques have been used successfully to detect flaws within concrete; however, no standardized method currently exists for pulse-echo evaluation of concrete structures. Based on the current state of knowledge, areas of needed research are outlined.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

acoustics; concrete; integrity testing; nondestructive testing; pulse-echo method; wave propagation.

13. AVAILABILITY

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