THE IMPACT-ECHO METHOD: AN OVERVIEW

by

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The Impact-Echo Method: An Overview[1]

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Abstract

The impact-echo method is a technique for flaw detection in concrete. It is based on monitoring the surface motion resulting from a short-duration mechanical impact. The method overcomes many of the barriers associated with flaw detection in concrete based on ultrasonic methods. The purpose of this paper is to provide an overview of the technique and to discuss the important parameters involved in this type of testing. One of the key features of the method is the transformation of the recorded time domain waveform of the surface motion into the frequency domain. The impact gives rise to modes of vibration and the frequency of these modes is related to the geometry of the test object and the presence of flaws. The principles involved in frequency analysis are discussed. The importance of the impact duration in relation to flaw detection and other factors affecting the smallest flaw that can be detected are also reviewed. The paper concludes with a summary of the ASTM standard governing the use of the impact-echo method for measuring the thickness of plate-like structures.

Introduction

The National Institute of Standards and Technology (NIST) (formerly known as the National Bureau of Standards (NBS)) has historically provided the basis for measurements in the area of public health and safety. Nondestructive testing (NDT) plays a key role in assuring the adequacy of manufactured components, and has been a core research area at NBS/NIST for many years. Research conducted in the 1940s to the 1960s provided the technical basis for standards on classical NDT methods employed routinely by industry, such as X-ray radiography, ultrasonic methods, eddy current methods, and magnetic methods. Little work, however, was conducted on NDT methods for concrete structures. In the late 1970s, two major construction failures were investigated by NBS [Carino et al., 1983; Lew, 1980]. In both cases, the in-place concrete strength was identified as a contributing factor to the accidents. These disastrous construction failures raised serious questions about the adequacy of existing technology to assure safety in concrete construction. As a result, the NBS undertook a long-term research program to provide the technical basis for test methods to evaluate the in-place characteristics of concrete. The initial work dealt with methods to estimate the development of concrete strength during construction, which is the most vulnerable stage in the life of typical concrete structures. This work culminated in the development of draft standards, guidelines, and statistical tools that were eventually adopted by ASTM and the American Concrete Institute [ASTM C 1074, ACI 228.1R].

Beginning in 1983, the focus of NBS research on NDT of concrete shifted toward the detection of internal defects. Based on a review of available methods, it was decided to pursue a test method based on stress waves, since stress wave propagation in a solid is affected directly by mechanical properties [Carino and Sansalone 1984]. The technique that was developed became known as the *impact-echo method* [Sansalone and Carino, 1986]. The initial research provided the basis for the technique and demonstrated its capability to detect flaws in plate-like structures. The research involved a combination of numerical simulations using the finite-element method and controlled-flaw studies to arrive at the most suitable testing configuration. Beginning in 1987, research shifted to Cornell University, under the direction of Professor Mary Sansalone, who participated in the groundbreaking work at NBS as a PhD student. The Cornell research expanded the applicability of the method and resulted in the development of the first patented field instrument [Pratt and Sansalone, 1992]. In addition, Sansalone and Streett [1997] produced a book that provides a comprehensive summary of the results of analytical, laboratory, and field studies dealing with different applications of the method. The book also provides practical guidelines for field-testing. In the late 1990s, NIST and Cornell cooperated on the development of a draft standard test method on the application of the impact-echo method. ASTM adopted the standard in 1998 [ASTM C 1383].

The early successes leading to the impact-echo method resulted from a combination of factors [Sansalone, 1997]. First, the NBS research team was composed of individuals with different capabilities and backgrounds, who were able to make key contributions toward solving the problem. Second, the availability of numerical modeling tools permitted the researchers to simulate stress wave propagation under different test conditions. The numerical simulations established the theoretical basis for the method and permitted the development of optimum testing configurations. Third, a new displacement transducer, which was developed at NBS for a different purpose [Proctor, 1982], turned out to be ideal for impact-echo testing. Fourth, the researchers took advantage of developments in signal processing and used frequency analysis of the recorded signals, which simplified greatly the interpretation of test results [Carino et al. 1986b]. Finally, the basic capabilities of the method were established by a combination of numerical studies and companion controlled-flaw studies [Sansalone and Carino, 1988a, 1988b]. Preliminary research also demonstrated the feasibility of using impact-echo testing to monitor setting and early-age strength development of concrete [Pessiki and Carino, 1988].

The purpose of this paper is to review the principles of the impact-echo method, including the fundamental relationships of wave propagation in a solid. This is followed by discussion of the basic elements of the impact-echo method and the factors affecting the smallest flaw that can be detected. The paper concludes with a summary of the ASTM standard governing the use of the method for thickness measurement.

Background

Tapping an object with a hammer is one of the oldest forms of nondestructive testing based on stress wave propagation. Depending on whether the result is a high-pitched “ringing” sound or a low frequency “rattling” sound, the integrity of the member can be assessed. The method is subjective, as it depends on the experience of the operator, and it is limited to detecting near surface defects. Despite these inherent limitations, *sounding* is a useful method for detecting near-surface delaminations, and it has been standardized by ASTM [D 4580].

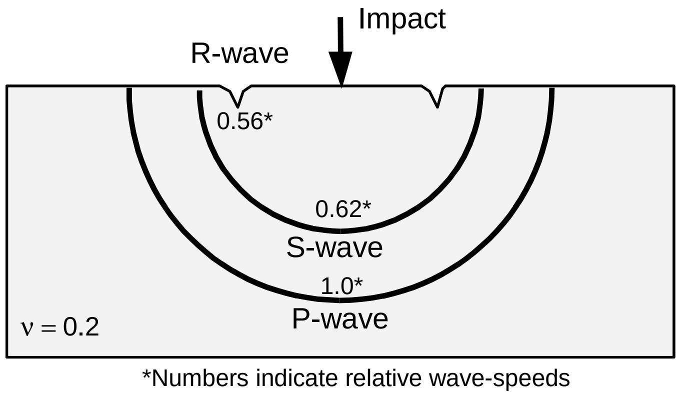

Fig. 1—Stress waves caused by impact at a point on the surface of a concrete plate.

In nondestructive testing of metals, the *ultrasonic pulse-echo* (UP-E) technique has proven to be a reliable method for locating cracks and other internal defects. An electro-mechanical transducer is used to generate a short pulse of ultrasonic stress waves that propagates into the object being inspected. Reflection of the stress pulse occurs at boundaries separating materials with different densities and elastic properties. The reflected pulse travels back to the transducer that also acts as a receiver. The received signal is displayed on an oscilloscope, and the round trip travel time of the pulse is measured electronically. By knowing the speed of the stress wave, the distance to the reflecting interface can be determined.

Attempts to use UP-E equipment designed for metal inspection to test concrete have been unsuccessful because of the heterogeneous nature of concrete [Carino and Sansalone, 1984]. The presence of paste-aggregate interfaces, air voids, and reinforcing steel results in a multitude of echoes that obscure those from real defects. In the last 10 to 20 years, however, there has been considerable progress in the development of usable techniques based on the propagation of lower frequency waves resulting from mechanical impact [ACI 228.2R]. This section reviews the basic concepts of stress-wave propagation that underlie these impact methods, including the impact-echo method (see Sansalone and Carino [1991] and Sansalone and Streett [1997] for more comprehensive discussions).

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Basic relationships **—** When a disturbance (stress or displacement) is applied suddenly at a point on the surface of a solid, such as by impact, the disturbance propagates through the solid as three different types of stress waves: a P-wave, an S-wave, and an R-wave. As shown in Fig. 1, the P-wave and S-wave propagate into the solid along spherical wave fronts. The P-wave is associated with the propagation of normal stress and the S-wave is associated with shear stress. In addition, there is an R-wave that travels away from the disturbance along the surface. Figure 2 shows the results of a finite-element analysis of the impact response of a plate [Sansalone and Carino, 1986]. The figure is a plot of the nodal displacements of the finite element mesh. At this point in the analysis the S-wave is arriving at the bottom of the plate and the P-wave reflection is about halfway up the plate. The locations of the various wave fronts are seen clearly. Numerical simulations of this type were carried out at NBS and provided invaluable insight into the impact response of solid and flawed plates [Sansalone and Carino, 1986, 1987; Sansalone et al., 1987a, 1987b].

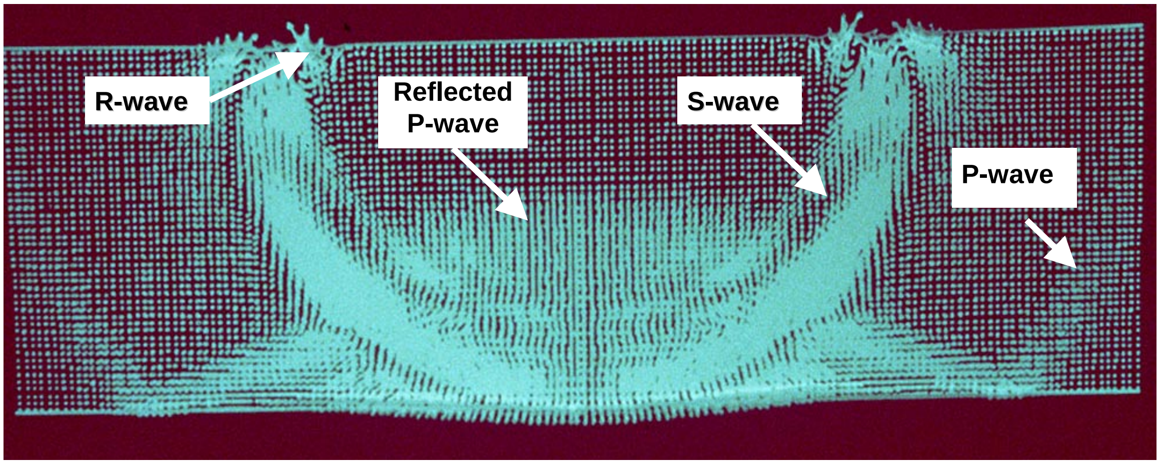


Fig. 2—Finite element simulation of impact on a plate; at this point in the analysis the S-wave front is arriving at the bottom of the plate and the P-wave has reflected halfway up the plate.

In an infinite isotropic, elastic solid, the P-wave speed, C_p, is related to the Young's modulus of elasticity, E, Poisson's ratio, ν, and the density, ρ, as follows [Krautkrämer and Krautkrämer, 1990]:

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

The S-wave propagates at a slower speed, C_s, given by

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

where G = the shear modulus of elasticity.

The ratio of S-wave speed to P-wave speed depends on Poisson's ratio as follows:

$$\frac{C_s}{C_p} = \sqrt{\frac{1-2\nu}{2(1-\nu)}} \tag{3}$$

For a Poisson's ratio of 0.2, which is typical of concrete, this ratio equals 0.61. The ratio of the R-wave speed, C_r, to the S-wave speed is given by the following approximate formula:

$$\frac{C_r}{C_s} = \frac{0.87+1.12\nu}{1+\nu} \tag{4}$$

For Poisson's ratio equal to 0.2, the R-wave speed is 92 % of the S-wave speed.

Reflection at interface—When a stress wave traveling through material *1* is incident on the interface between a dissimilar material *2*, a portion of the incident wave is reflected. The amplitude of the reflection is a function of the angle of incidence and is a maximum when this angle is 90° (normal incidence). For normal incidence the reflection coefficient, R, is given by the following [Krautkrämer and Krautkrämer, 1990]:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{5}$$

where

Z_2 = specific acoustic impedance of material 2 and
Z_1 = specific acoustic impedance of material 1.

The specific acoustic impedance is the product of the wave speed and density of the material. The following are approximate *Z*-values for some materials [Sansalone and Carino, 1991]:

Material	Specific acoustic impedance, kg/(m^2 s)
Air	0.4
Water	0.5 x 10^6
Soil	0.3 to 4 x 10^6
Concrete	7 to 10 x 10^6
Steel	47 x 10^6

Thus, when a stress wave traveling through concrete encounters an interface with air, there is almost total reflection at the interface. This is why NDT methods based on stress wave propagation have proven to be successful for locating defects within solids.

The reflection coefficient given by Eq. (5) can be negative or positive depending on the relative values of the acoustic impedances of the two materials. If $Z_2 < Z_1$, such as would occur at a concrete-air interface, the reflection coefficient is negative. This means that the sign of the stress in the reflected wave is opposite to the sign of the stress in the incident wave. Thus an incident P-wave with a compressive stress would reflect as a P-wave with a tensile stress. If $Z_2 > Z_1$, the reflection coefficient is positive and there is no change in the sign of the stress. In this case, an incident P-wave with compressive stress would reflect back a wave with compressive stress. These differences are important in distinguishing between reflection from a concrete-air interface and from a concrete-steel interface [Sansalone and Carino, 1990; Cheng and Sansalone, 1993b].

Impact-echo Method

The greatest success in the practical application of stress wave methods for flaw detection in concrete has been to use mechanical impact to generate the stress pulse. Impact produces a high-energy pulse that can penetrate deep into concrete. The first successful applications of impact methods occurred in geotechnical engineering to evaluate the integrity of concrete piles and caissons [Steinbach and Vey, 1975]. The technique became known as the *sonic-echo* or *seismic-echo* method [ACI 228.2R]. The long length of these foundation structures allowed sufficient time separation between the generation of the impact and the echo arrival, and determination of round-trip travel times was relatively simple [Lin et al., 1991b; Olson and Church, 1986]. The impact response of thin concrete members, such as slabs and walls, is more complicated than that of long slender members. Work by Sansalone and Carino [1986], however, led to the

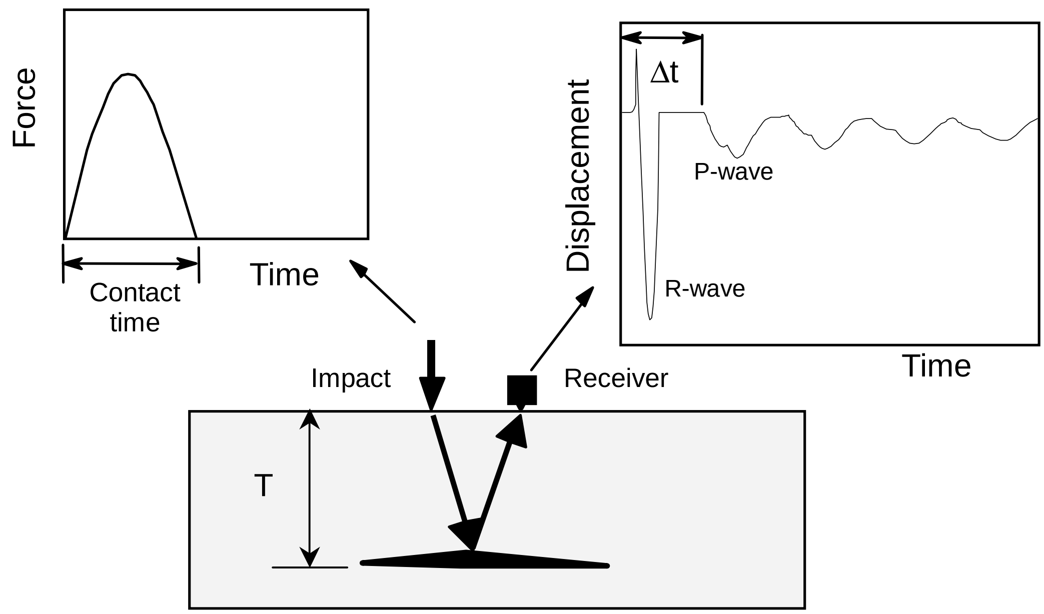


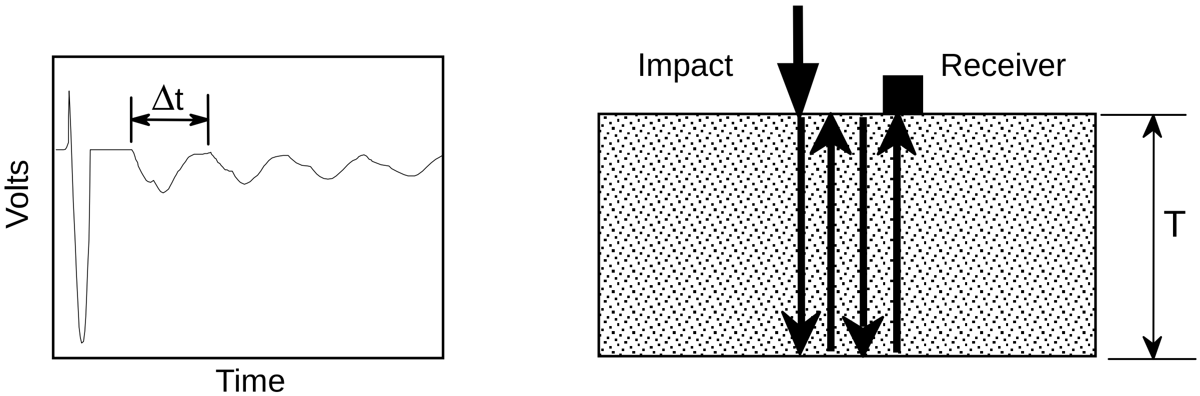
Fig. 3— The impact-echo method: mechanical impact is used to generate stress waves and a receiver next to the impact point measures the resulting surface motion.

development of the *impact-echo method*, which has proven to be a powerful technique for flaw detection in relatively thin concrete structures.

Figure 3 is a schematic of an impact-echo test on a plate with a large air void below the surface. As was discussed, impact on the surface produces P- and S-waves that travel into the plate and a surface wave (R-wave) that travels away from the impact point. The P- and S-waves are reflected by internal defects (difference in acoustic impedance) or external boundaries. When the reflected waves, or echoes, return to the surface, they produce displacements that are measured by a receiving transducer. If the transducer is placed close to the impact point, the response is dominated by P-wave echoes [Sansalone and Carino, 1986]. The right hand side of Fig. 3 shows the pattern of surface displacements that would be occur. The large downward displacement at the beginning of the waveform is caused by the R-wave, and the series of repeating downward displacements of lower amplitude are due to the arrival of the P-wave as it undergoes multiple reflections between the surface and the internal void.

Frequency analysis—In the initial work leading to the impact-echo method, *time domain* analysis was used to measure the time from the start of the impact to the arrival of the P-wave echo [Carino et al., 1986a]. While this was feasible, the process was time consuming and required skill to properly identify the time of P-wave arrival. A key development leading to the success of the impact-echo method was the use of *frequency analysis* instead of time domain analysis of the recorded waveforms [Sansalone and Carino, 1986; Carino et al., 1986b].

The principle of frequency analysis is illustrated in Fig. 4. The P-wave produced by the impact undergoes multiple reflections between the test surface and the reflecting interface. Each time the P-wave arrives at the test surface, it causes a characteristic displacement. Thus the waveform has a periodic pattern that depends on the round-trip travel distance of the P-wave. If



$$\Delta t = \frac{2T}{C_{pp}} \qquad\qquad f = \frac{1}{\Delta t} = \frac{C_{pp}}{2T}$$

Fig. 4— Principle of frequency analysis: the time domain waveform has a periodic pattern due to P-wave arrival as it undergoes multiple reflections between the top and bottom of the plate; the frequency of P-wave arrival is related directly to the plate thickness.

the receiver is close to the impact point, the round trip travel distance is 2*T*, where *T* is the distance between the test surface and reflecting interface. As shown in Fig. 4, the time interval between successive arrival s of the multiply reflected P-wave is the travel distance divided by the wave speed. The frequency, *f*, of the P-wave arrival is the inverse the time interval and is given by the approximate relationship:

$$f = \frac{C_{pp}}{2T} \tag{6}$$

where

C_{pp} = the P-wave speed through the thickness of the plate,
T = the depth of the reflecting interface.

If the test object is a solid plate, the frequency calculated according to Eq. (6) is called the *plate thickness frequency*.

Equation (6) is the basic relationship for interpreting the results of impact-echo tests. In the early research leading to the development of the impact-echo method, it was assumed that the wave speed across the thickness of the plate was the same as the P-wave speed in a large solid, as given by Eq. (1) [Sansalone and Carino, 1986]. Subsequent and more rigorous studies, however, have shown that the apparent wave speed relating the thickness frequency and plate thickness is approximately 96 % of the P-wave speed, that is, C_{pp} = 0.96 C_p [Lin and Sansalone, 1997]. According to Sansalone and Streett [1997]: *"…this difference occurs because multiple reflections of P-waves excite a particular mode of vibration in the plate—the thickness mode—and the displacements caused by this mode produce the principal periodic patterns in the waveform."*

Amplitude spectrum**—**In frequency analysis of impact-echo results, the objective is to determine the dominant frequencies in the recorded waveform. This is accomplished by using the fast Fourier transform technique to transform the recorded waveform into the frequency domain

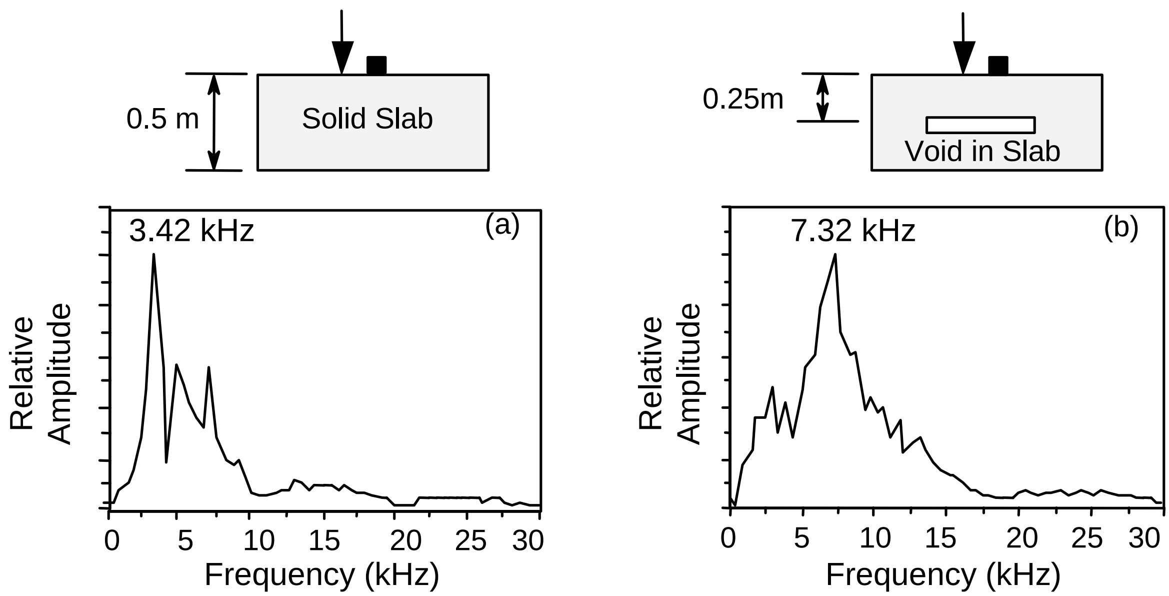


Fig. 5— Examples of amplitude spectra from impact-echo tests: a) test of solid portion of a 0.5 m thick slab and b) test over an artificial void approximately 0.25 m deep.

[Bracewell, 1978]. The transformation results in an amplitude spectrum that shows the amplitudes of the various frequencies contained in the waveform. For plate-like structures, the thickness frequency will usually be the dominant peak in the spectrum. The value of the peak frequency in the amplitude spectrum can be used to determine the depth of the reflecting interface by expressing Eq. (6) as follows:

$$T = \frac{C_{pp}}{2f} \tag{7}$$

Figure 5 illustrates the use of frequency analysis of impact-echo tests. Figure 5(a) shows the amplitude spectrum from a test over a solid portion of a 0.5 m thick concrete slab. There is a frequency peak at 3.42 kHz, which corresponds to multiple P-wave reflections between the bottom and top surfaces of the slab. Using Eqs. (6) or (7) and solving for C_{pp}, the P-wave speed in the slab is calculated to be 3420 m/s. Figure 5(b) shows the amplitude spectrum from a test over a portion of the slab containing a disk-shaped void [Sansalone and Carino, 1986; Carino and Sansalone, 1990]. The peak at 7.32 kHz results from multiple reflections between the top of the slab and the void. Using Eq. (7), the calculated depth of the void is 3420/(2 x 7320) = 0.23 m, which compares favorably with the known distance of 0.25 m.

Instrumentation—Impact-echo testing relies on three basic components:

- A mechanical impactor capable of producing short-duration impacts, the duration of which can be varied,
- A high-fidelity receiver to measure the surface response, and
- A data acquisition-signal analysis system to capture, process, and store the waveforms of surface motion.

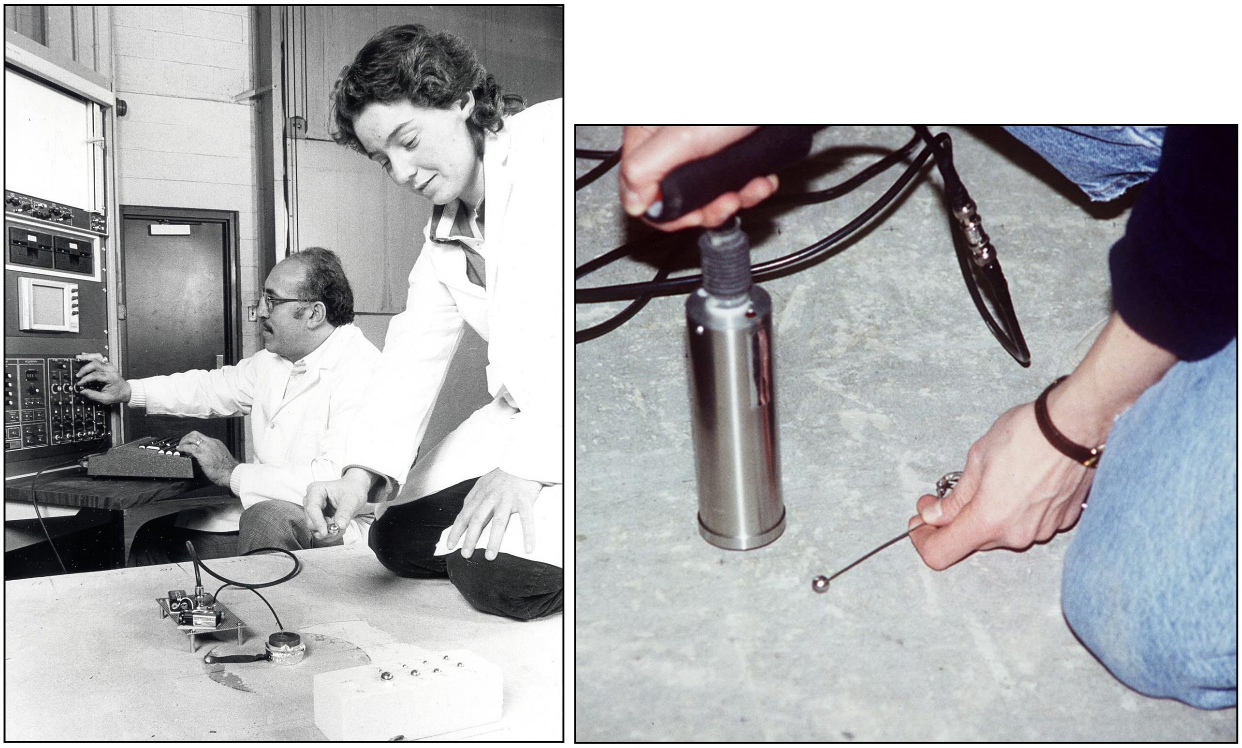


Fig. 6— (Left) In the early research steel balls were used to obtain impacts with different contact times; (Right) steel balls mounted on spring-steel rods are suited for field-testing.

In the initial NBS research, steel balls were dropped onto the concrete surface to produce the impact (Fig.6). Steel balls are convenient impact sources because impact duration is proportional to the diameter of the ball [Goldsmith, 1965]. The importance of impact duration is discussed in the next section. Subsequent development at Cornell University lead to the use of steel balls attached to spring-steel rods (Fig. 6). The latter system permits testing for any orientation of the surface.

The NBS researchers used a high-fidelity displacement transducer that had been developed for accurate measurement of acoustic emission waveforms [Proctor 1982]. The transducer is composed a small piezoelectric element bonded to a large brass block. While others have successfully used accelerometers for the same purpose [Olson 1992], the author believes a displacement transducer simplifies signal interpretation, because most of the theoretical studies of the impact-echo method have dealt with surface displacement [Sansalone and Streett, 1997]. The transducer must not have a resonant frequency that is close to the thickness frequencies that may be encountered during testing.

In order to accurately measure the surface motion, the transducer has to be coupled effectively to the concrete surface. For most transducers, some type of grease-like material is often used as a couplant. Sansalone and Carino [1986], however, used a thin lead strip as the coupling medium for the NBS point transducer (Fig. 7). The soft lead conforms to the irregular surface texture and transfers the surface motion to the piezoelectric element. This approach reduces the time needed to conduct a test.

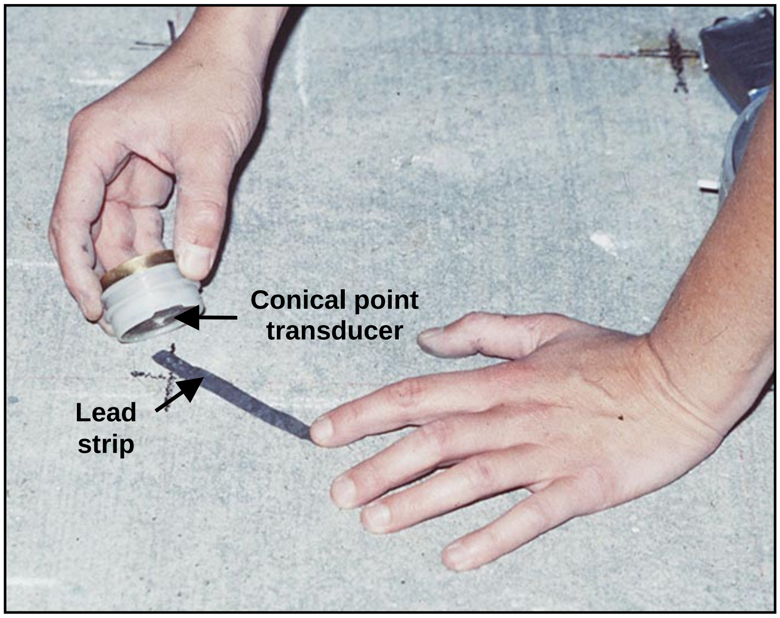


Fig. 7— The NBS conical point displacement transducer being coupled to a concrete surface using a thin lead strip.

The distance between the impact point and transducer is important. If the distance is too large, the response is not dominated by the reflected P-wave, and the simple relationships expressed by Eqs. (6) and (7) are not applicable. If the distance is too small, the response is dominated by the effect of the surface wave. Based on a series of analytical studies, spacing from 0.2 to 0.5 of the flaw depth was found to give acceptable results [Carino et al. 1986b]. Sansalone and Streett [1997] recommend a spacing of less than 40 % of the depth.

In the early research, displacement waveforms were captured and analyzed with a dynamic signal analyzer (see Fig. 6, left photo). Modern impact-echo instruments are based on portable computers with data acquisition cards and accompanying software. Figure 8 shows the three components of a commercial impact-echo test system being used to test the web of a reinforced concrete beam.

Impact duration**—**The duration of the impact is critical for the success of an impact- echo test. The basic idea of impact-echo testing is to create a resonant vibration corresponding to the thickness mode. In order to excite the thickness mode, the input pulse must contain the correct frequency component. As shown in Fig. 3, the force-time relationship for the impact may be approximated as a half-cycle sine curve, and the duration of the impact is the *contact time*. The frequency components contained in the input pulse can be determined from the Fourier transform of a half-cycle sine curve. It turns out that the transform can be expressed in closed form [Bracewell, 1978; Carino et al., 1986b]. Figure 9 shows the amplitude spectrum of a half-cycle sine curve. The spectrum is normalized to the contact time of the pulse. The amplitude of the frequency components is proportional to the contact time, and the range of the frequencies contained in the pulse is proportional to the inverse of the contact time. As an approximation, the highest frequency component of significant amplitude can be taken as the inverse of the contact

Fig. 8— Example of PC-based impact-echo test equipment (courtesy of Impact-Echo Instruments, LLC).

time. Thus as the contact time decreases, the range of frequencies increases but the amplitudes of the frequency components decrease.

In order to be able to detect shallow defects, the stress pulse must have frequency components greater than the frequency corresponding to the flaw depth (Eq. (6)). For example, for a P-wave speed of 4000 m/s and a flaw depth of 0.2 m, the thickness frequency is 10 kHz. Therefore the contact time of the pulse has to be shorter than about 100 µs to "see" the defect in the amplitude spectrum. As mentioned in the previous section, steel balls are effective impactors for field-testing because the contact time can be changed simply by using a different diameter ball. Sansalone and Streett [1997] provide guidance on factors to consider when selecting the most appropriate contact time during field tests. The contact time in an impact-echo test can be estimated by measuring the width of the initial "depression" in the time domain waveform, which corresponds to the width of the R-wave [Sansalone and Carino, 1986].

***Smallest detectable flaw*—**A common question about the impact-echo method is: "What is the smallest flaw that can be detected." The answer is not simple, because there are several factors that affect whether a given flaw can be detected, among them, are the following:

- The type of flaw and its orientation;
- The depth of the flaw;
- The contact time of the impact.

In addition, it is necessary to make a distinction between being able to "detect" the presence of a flaw and being able to determine the depth of the flaw. As discussed in Sansalone and Streett [1997], the presence of a small flaw may affect the thickness frequency response by shifting it to

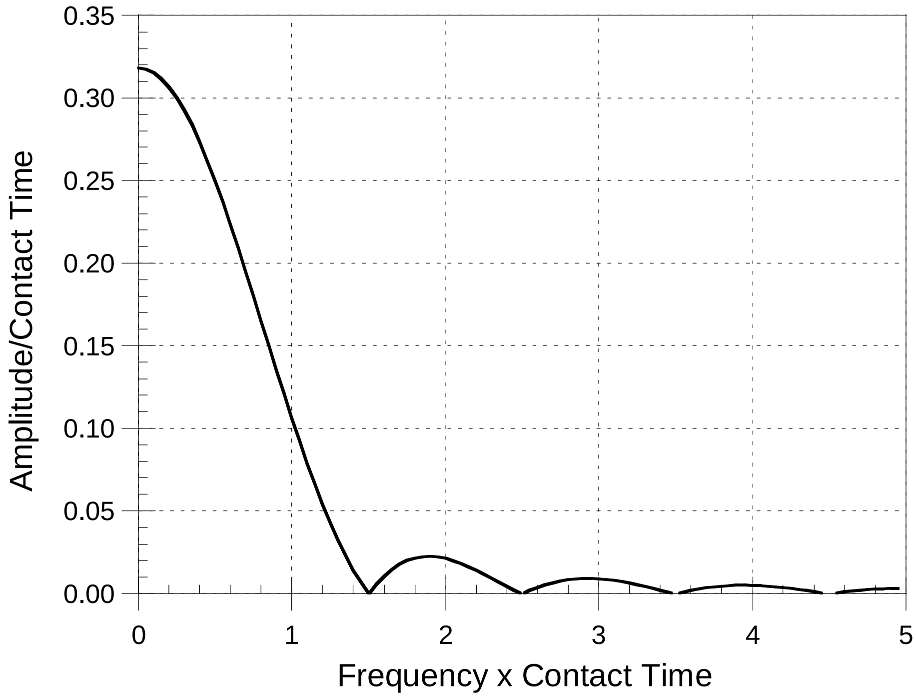


Fig. 9— Normalized amplitude spectrum for an impact having the shape of a half-cycle sine curve

a lower value. Thus, if the member thickness is known to be constant and there is no reason to suspect a difference in P-wave speed at different locations, an observed reduction in the thickness frequency is a reliable indicator that a flaw is present, even if the amplitude spectrum does not have a higher frequency peak corresponding to the flaw depth.

The easiest type of flaw to detect is a planar concrete-air interface that is parallel to the test surface, such as delaminations and voids. The presence of extensive air voids along an interface, although not presenting a continuous air interface, can also be detected, such as honeycombing or entrapped air at a concrete-overlay boundary [Sansalone and Carino, 1988; Lin and Sansalone, 1996].

As the depth of a flaw increases, the smallest size that can be detected also increases. Based on analytical and laboratory studies, Sansalone and Streett [1997] suggest that if the lateral dimensions of a planar crack or void exceed 1/3 of its depth, the flaw depth can be measured. If the lateral dimensions exceed 1.5 times the depth, the flaw behaves as an infinite boundary and the response is that of a plate with thickness equal to the flaw depth (Fig. 10). When a flaw falls within the cross-hatched region shown in Fig. 10, the amplitude spectrum will typically have two peaks: a higher frequency peak corresponding to the depth of the flaw and lower frequency peak corresponding to the plate thickness. As mentioned above, the thickness frequency will be shifted to a lower value than for the unflawed plate.

While the presence of a planar defect lying within the crosshatched region in Fig. 10 can be detected, its depth can be measured only if the contact time of the impact is sufficiently short. If the contact time is too long, there will be insufficient energy at the frequency corresponding to the thickness frequency (Eq. (6)), and the amplitude spectrum will not have a peak corresponding to the flaw depth. In general, the contact time needs to be shorter than the round trip travel time

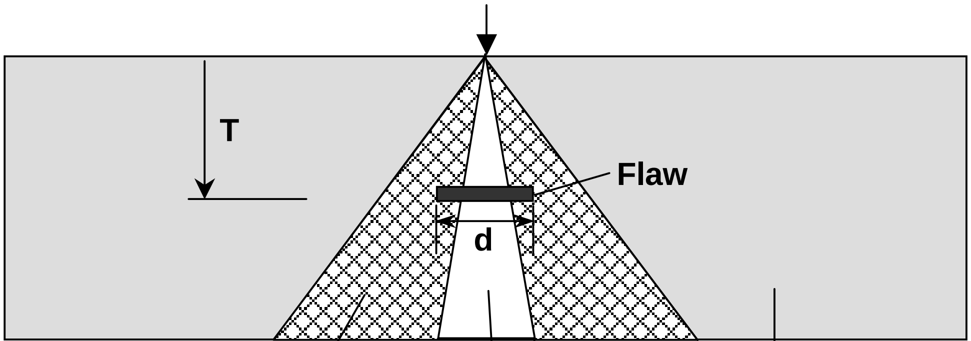


Fig. 10—The smallest detectable horizontal crack or void depends on its depth; if the flaw falls within the white region, its depth cannot be measured (based on Sansalone and Streett [1997]).

for the P-wave reflected from the flaw. In the original study by Sansalone and Carino [1986], it was found that if the contact time was less than ¾ of the P-wave travel time, the depth of a planar flaw of sufficient size could always be measured. Abraham et al. [2000] have also discussed the effects of flaw size and flaw depth, and their conclusions are in agreement with those presented here.

Applications

The impact-echo method has been successful in detecting a variety of defects, such as voids and honeycombed concrete in structural members, delaminations in bare and overlaid slabs, and voids in tendon ducts [Carino and Sansalone, 1992; Jaeger et al., 1996, 1997; Sansalone and Carino, 1986, 1988a, 1988b, 1989; Sansalone et al. 1991]. Experimental studies have been supplemented with analytical studies to gain a better understanding of the propagation of transient waves in bounded solids with and without flaws [Cheng and Sansalone 1993a, 1993b, 1995a, 1995b; Sansalone and Carino, 1987; Lin et al., 1991a, 1991b; Sansalone et al., 1987a, 1987b].

Application of the method has been extended to prismatic members, such as columns and beams [Lin and Sansalone, 1992a, 1992b, 1992c]. It has been found that reflections from the perimeter of these members cause complex modes of vibration. Figure 11 shows an example of the shapes associated with the modes of vibration of a square beam or column [Lin and Sansalone, 1992b]. These modes result in an amplitude spectrum with many peaks, and the depth of the member is not related to the dominant frequency in the spectrum according to Eq. (7). Nevertheless, it has been shown that defects can still be detected within beams and columns, and successful field applications have been reported [Poston and Sansalone, 1997; Sansalone and Streett, 1997]. In order to avoid the complexities associated with these cross-sectional modes, the smallest lateral dimension of the structure should be at least fives times the thickness [Sansalone and Streett, 1997].

The impact-echo method has also been applied to evaluate the quality of the bond between an overlay and base concrete [Lin and Sansalone, 1996, Lin et al., 1996]. While it is not possible to

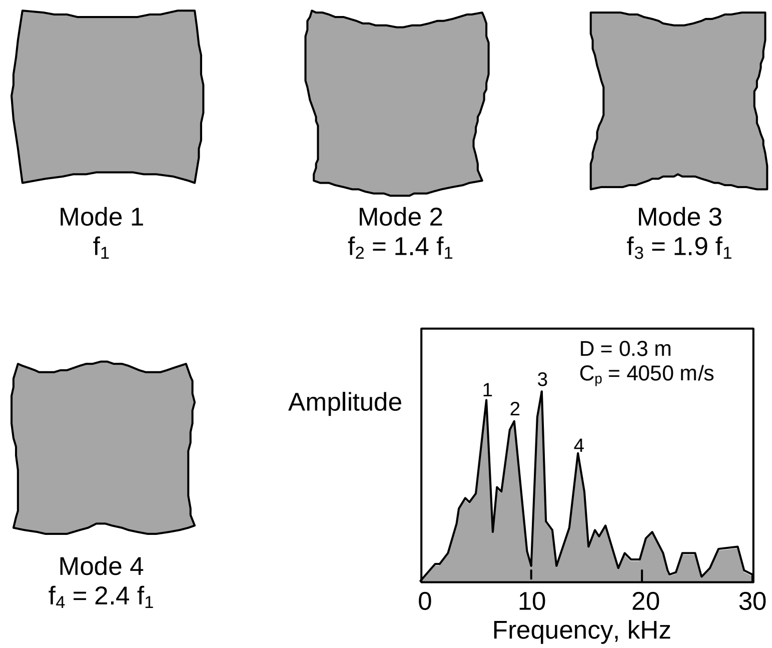


Fig. 11—The first 4 mode shapes and corresponding experimental amplitude spectrum for a solid 0.3 m square bar (based on Lin and Sansalone 1992b).

estimate the bond strength, the impact-echo method may determine whether there is extensive porosity at the interface.

ASTM Test Method C 1383

The development of a standard test method for flaw detection using impact-echo is difficult because of the many variables that may be encountered in field-testing. The types of defects can vary from the rather simple case of delaminations or voids to the complex case of distributed microcracking. The type of structure can vary from the simple case of a slab to the complex case of a round column. The measurement of the thickness of a plate-like structure, however, is a relatively straightforward application that is amenable to standardization. In 1998, ASTM adopted a test method on the use of the impact-echo method to measure the thickness of plate-like concrete members. In this case, a plate is defined as a structure or portion of a structure in which the lateral dimensions are at least six times the thickness.

ASTM C 1383 includes two procedures. Procedure A, which is shown in Fig. 12(a), is used to measure the P-wave speed in the concrete. This measurement is based on measuring the travel time of the P-wave between two transducers a known distance apart. The background research for this technique is provided in Sansalone et al. [1997a, 1997b]. Procedure B (Fig. 12(b)) is to determine the thickness frequency using the impact-echo method from which the plate thickness is calculated using the measured P-wave speed and Eq. (7). Note that the P-wave speed obtained by Procedure A is multiplied by 0.96 when used in Eq. (7). The data analysis procedure considers the systematic errors associated with the digital nature of the data in Procedures A and B. The thickness is reported with an uncertainty that is related to the sampling interval in Procedure A and the duration of the recorded signal in Procedure B [Sansalone et al., 1997a, 1997b]. Limited

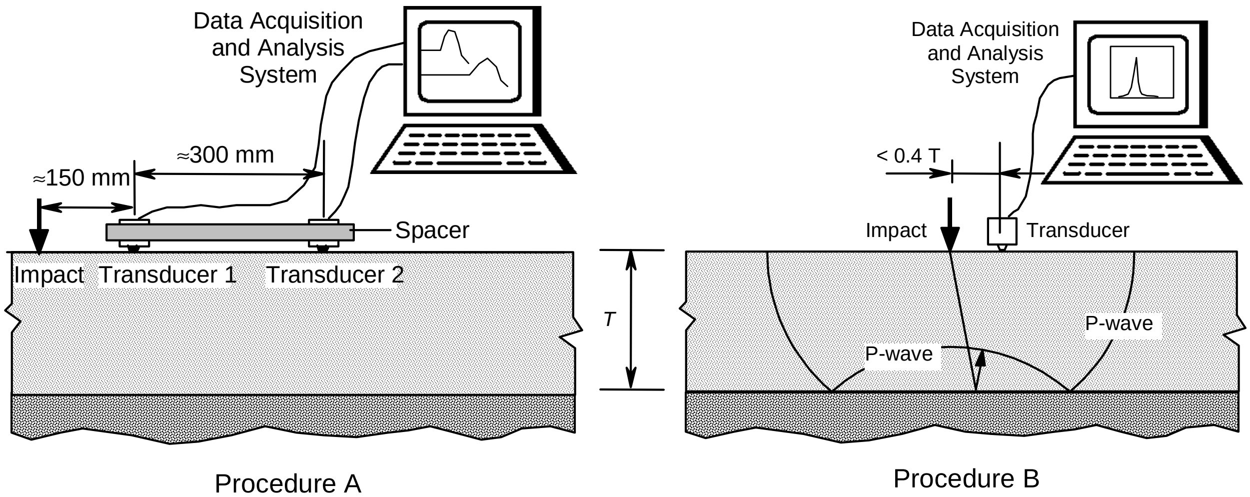


Fig. 11—Two-step procedure for measuring plate thickness according to ACTM C 1383: Procedure A is used to determine the P-wave speed and Procedure B is used to determine the thickness frequency.

comparisons with the length of drilled cores demonstrated that the impact-echo results were within 3 % of the core lengths [Sansalone et al., 1997b; Sansalone and Streett, 1997].

Summary

The impact-echo method is proving to be a reliable method for locating a variety of defects in concrete structures. The success is, in part, a result of its well-founded scientific basis derived from a prolonged research effort that combined theory, numerical simulation, experimental verification, and field demonstrations. This paper provides basic information about the major principles underlying impact-echo testing. As with most methods for flaw detection in concrete, experience is required to interpret impact-echo test results. While the use of frequency analysis has aided in interpreting test results, experience is needed in setting up optimal testing parameters, recognizing valid recorded waveforms, and analyzing test results.

Because of the varied situations that may be encountered in field-testing, a standard test method for flaw detection has yet to be developed. There is, however, an ASTM test method on measuring the thickness of plate-like structures. Much of the guidance in ASTM C 1383 is useful for the more general case of flaw detection. Sansalone and Street [1997] provide useful tips for planning and conducting a successful impact-echo investigation. Their concluding advice is that any impact-echo investigation should include verification at selected points to instill confidence in the method.

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