Laboratory and Field Studies of the Impact-Echo Method for Flaw Detection in Concrete

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Synopsis: A nondestructive test method has been developed for locating defects in concrete. The technique is referred to as the impact-echo method and is based on monitoring surface displacements resulting from the interactions of transient stress waves with internal discontinuities. This paper describes the technique and presents results of laboratory studies designed to evaluate the capabilities of the method. These laboratory studies were carried out on 500-mm thick slabs which contained a variety of artificial flaws embedded at known locations. Frequency analysis of recorded time-domain waveforms is explained and shown to be a quick and simple signal processing technique. Finally, results are presented from a field study in which the impact-echo method was used to investigate a 150-mm thick slab believed to contain voids.

Keywords: concretes; concrete slabs; impact; nondestructive tests; ultrasonic tests; voids

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INTRODUCTION

A nondestructive testing technique for locating flaws within concrete has been developed at the National Bureau of Standards (NBS) [1-4]. The technique involves introducing transient stress waves into a test object by mechanical impact and monitoring the dynamic displacements caused by the arrival of waves reflected from internal defects and external boundaries. A transducer located close to the impact point is used to monitor the surface displacement. Previously referred to as a pulse-echo method, the technique has come to be called the **impact-echo method**. The name "impact-echo" was adopted to distinguish the technique from traditional ultrasonic pulse-echo techniques in which one piezoelectric transducer is used both to generate the stress pulse and to monitor reflections.

This paper describes significant improvements to the original measurement technique. Previously, recorded displacement waveforms were studied in the time domain and interpretation required determining the arrival times of wave reflections [1,2]. This time-consuming process has been replaced by frequency analysis, a simpler and more efficient method for data interpretation. In addition, this paper presents the results of laboratory studies using plain and reinforced concrete plates with known flaws and results obtained from a field study of an ice-skating rink slab containing voids.

Although this paper focuses primarily on the impact-echo measurement technique and on experimental results, a major part of the NBS research program has been devoted to understanding the physics involved in the test method. Theoretical and finite element studies of transient stress wave propagation in bounded solids with and without flaws have been performed [3-8]. The understanding gained from these studies provided the theoretical basis for the interpretation of the test results which are presented in this paper.

IMPACT-ECHO METHOD

Measurement Technique

Figure 1 is a schematic representation of point impact on a plate containing a flaw at a depth T. Initially, small steel ball bearings dropped from a height of 100 to 200 mm were used as the impact source. In current work, spring-loaded impactors, which have spherically-tipped, impacting masses of 3, 5.5 and 20 g, are also used as impact sources. The force-time history of an elastic impact may be approximated as a half-sine curve, and the duration of the impact is the "contact time." The contact times produced by the ball bearings and impactors ranged from approximately 20 to 90 microseconds. The contact time is an important variable in impact-echo testing because it determines the frequency content of the input pulse [4]. The frequency content affects the size of the defect that can be detected [3]. As the contact time decreases, smaller defects can be detected and defects near the surface can be accurately located. However, as contact time decreases the penetrating ability of the stress waves also decreases. Therefore, the selection of a contact time will depend upon the intent of the particular testing situation and the flaw size to be detected.

The receiving transducer is a broadband displacement transducer which consists of a small, conically-shaped, piezoelectric element cemented to a large brass backing [2,10]. The output of this transducer is proportional to normal surface displacement. The transducer was developed for use on metal objects. In initial studies, a thin sheet of aluminum foil was used between the conical element and the concrete surface to complete the transducer circuit [1,2]. The foil was coupled to the concrete using water soluble gel, and the tip of the transducer rested directly on the foil. Grinding of the concrete was generally required to achieve proper coupling between the conical element and the surface. In current studies, the foil and gel have been replaced with a thin sheet of lead. Use of the lead, which is malleable and conforms to the concrete surface, eliminates the need for surface preparation and simplifies the experimental procedure.

In current work, the transducer is used with a high-pass filter that strongly attenuates frequencies less than 2 kHz. The filter was added to reduce the effects caused by a low frequency resonance of the transducer assembly (the large brass backing on the small conical element behaving like a mass on a spring). The use of the filter clarifies displacement waveforms and simplifies their interpretation.

Frequency Analysis

Point impact on a solid generates a stress pulse. This pulse produces compression (P) and shear (S) waves which propagate into the solid along spherical wavefronts, and a Rayleigh (R) wave which propagates along the surface. The P- and S-waves are reflected from internal flaws and external boundaries. In time domain analysis of displacement waveforms, the arrival time of reflected waves must be determined [1,2,5,6]. To successfully identify wave arrivals, a short duration impact must be used, and the impact point and receiving transducer must be located sufficiently far from the edges of a test object so that R-wave reflections from the edges do not interfere with waves reflected from internal reflections. Time domain analysis was found to be time-consuming and difficult for all but the simplest geometries. These problems led to the use of frequency analysis as an alternative approach for interpretation of impact-echo waveforms [3,4,7,8].

An impact-echo test on a large diameter plate will be used to illustrate the principle of frequency analysis. Impact on the surface of the plate generates a stress pulse, which is reflected back and forth between the top and bottom surfaces of the plate. Thus a transient resonance condition is created. For waveforms recorded close to the impact point, the P-wave portion of the pulse dominates the displacement waveform. Each time the P-wave arrives at the top surface of the plate it causes a downward displacement [2,3], and the waveform exhibits a characteristic periodic pattern. The time between successive downward displacements is the time, Δt, it takes for the P-wave to propagate to the bottom of the plate and return to the top surface:

$$\Delta t = \frac{2T}{C_p} \qquad (1)$$

where T is the plate thickness, and C_p is the P-wave speed. The frequency of P-wave arrivals at the top surface is equal to the inverse of the travel time:

$$f = \frac{1}{\Delta t} = \frac{C_p}{2T} \qquad (2)$$

This equation can be rewritten to express the thickness as a function of P-wave speed and frequency:

$$T = \frac{C_p}{2f} \qquad (3)$$

Equation (3) is the basic relationship used in frequency analysis. If the P-wave speed in the plate is known and the frequency of P-wave arrivals can be determined, then the plate thickness can be calculated. This same analysis is applicable to reflections from internal flaws which also produce a transient resonance condition. Thus this is an alternative method for determining the thickness of test objects or the depth of flaws without having to identify wave arrival times.

The frequency content of displacement waveforms is determined using the principle of Fourier series which states that any waveform can be represented as a sum of sine curves, each with a particular amplitude, frequency, and phase shift. This transformation of the digitally recorded waveforms is carried out using the fast Fourier transform technique [11]. The resulting spectra show the amplitude and phase of each component frequency in the waveform.

In current work, analysis of the amplitude spectrum is used almost exclusively to interpret test results as it is quicker and simpler than time domain analysis. A waveform analyzer is used to store and process received signals. The fast Fourier transform is programmed into the waveform analyzer and the amplitude spectrum of a waveform can be obtained instantaneously. For the results presented in this paper, waveforms were recorded using a 2 microsecond sampling interval (500 kHz sampling frequency) and they contained 1024 sampling points. The digital spectra obtained from these waveforms had a frequency difference between adjacent points of 0.488 kHz.

CONTROLLED FLAW STUDIES

Frequency Analysis

To illustrate the application of frequency analysis, results are shown from impact-echo tests on a 500-mm thick concrete plate (2.0 x 4.5 m in plan) in which were embedded, at known locations, 25-mm thick, rigid polyurethane disks. These disks simulate planar flaws. This was the same test specimen used in the time domain studies presented in References [1,2]; concrete properties and plan and elevation views of the plate are given in these references.

A series of displacement waveforms (500 points shown) and their corresponding amplitude spectra are shown in Fig. 2. The waveform and spectrum in Fig. 2(a) were obtained over a 200-mm diameter disk located 127 mm below the top surface of the plate. Figures 2(b) and 2(c) were obtained over 500-mm diameter disks located 258 and 380 mm deep, and Fig. 2(d) was obtained over a solid portion of the plate. Notice how the peaks in the spectra shift from 14.2 kHz in Fig. 2(a) to 3.42 kHz in Fig. 2(d) as the depth of the interface increases from 127 to 500 mm. In Fig. 2(a) two peaks are evident. The lower frequency peak at 3.42 kHz corresponds to reflections from the bottom of the plate (compare Figs. 2(a) and (d)); this frequency will be referred to as the thickness frequency. In this case, the small diameter disk reflects the higher frequency components of the propagating waves; the lower frequency components with longer wavelengths, travel around the disk and are reflected at the bottom surface of the plate. Thus both reflecting interfaces can be identified in the spectrum.

Figure 3 shows the known depths of the disks plotted versus the inverse of twice the peak frequencies in the corresponding spectra. As expected from Eq. (3), the points fall approximately on a straight line; the slope of the best-fit line is the P-wave speed and has a value of 3530 m/s. In this case, the depths of all the interfaces were known. In actual testing, it is the depth of the interface that must be determined. Therefore, the P-wave speed in a test object must be a known.

Previously it was thought that the through-transmission, pulse-velocity method (ASTM C 597 [12]) could be used to independently measure the P-wave speed in concrete [1,2]. In the pulse-velocity method, a transmitting transducer and a receiving transducer are located on opposite sides of a test object, and the time for a pulse of ultrasonic waves to travel from the transmitter to the receiver is measured. The ultrasonic pulse velocity is obtained by dividing the distance between the transducers by the travel time. However, it was found that when the ultrasonic pulse velocity (obtained using 50-mm diameter, 54 kHz transducers) was used to calculate the depth of reflecting interfaces (Eq. 3), the calculated depths exceeded the actual depths. Direct comparisons were made between ultrasonic pulse velocities measured through the thickness of solid concrete plates and the P-wave speed calculated from the thickness frequencies obtained from impact-echo tests on the same plates. This comparison showed that the P-wave speeds calculated by the impact-echo method were approximately 10 percent slower than the ultrasonic pulse velocities. Reference [3] presents a detailed discussion of this discrepancy, which currently cannot be explained. The important point is that in impact-echo testing, the P-wave speed must be determined from an impact-echo test on a part of the structure where the thickness is known. This speed can then be used to accurately determine the depth of internal interfaces in other parts of the structure.

Effect of Reinforcing Steel

Figure 4 is a plan view of a 500-mm thick concrete plate (2.0 x 2.25 m in plan) which contained a variety of artificial flaws, including: a thin metal duct partially filled with grout; 0.075-mm thick plastic sheets to simulate cracks; and, circular and rectangular flaws cut from polyurethane foam board. A grid of steel reinforcing bars was placed over half the plate at a depth of 50 mm below the top surface; standard No. 7 and 8 bars (22.2 and 25.4 mm in diameter, respectively) were used. The coarse aggregate was crushed limestone with a nominal maximum size of 19 mm; the 28-day cylinder compressive strength was 28.4 MPa. The P-wave speed in the plate was obtained from an impact-echo test over a solid portion of the plate. (In this case, the sampling interval was 5 microseconds.) The thickness frequency was 4.1 kHz and the computed P-wave speed was 4100 m/s.

Preliminary studies of concrete plates containing only steel bars were carried out to gain an understanding of how reinforcing steel would effect the results of impact-echo tests [3]. Two important conclusions came out of this study:

(1) The frequency peak corresponding to reflections from a concrete/steel interface occurs at half the frequency value corresponding to reflections from a concrete/air interface. The explanation for this behavior has been presented [3]. Thus the apparent depth of a steel bar calculated using Eq. (3) is twice the actual depth.

(2) The contact time of the impact determines the effect of the steel bars on impact-echo results. If the primary intent of the testing is to locate reinforcing steel, short duration impacts must be used. Waves produced by shorter duration impacts contain significant high frequency (or shorter wavelength) components[1] [4]. These high frequency components will be reflected by the bars. If, however, the primary intent of the testing is to find flaws in reinforced concrete, the effects of the steel can be minimized by using impacts with longer contact times. Longer duration impacts will not contain the high frequency components that can be reflected by small diameter bars.

Voids in Reinforced Concrete

Figure 5 shows results obtained from a series of impact-echo tests along a section of the 500-mm thick reinforced concrete plate which contained two 200-mm diameter, disk-shaped flaws. Figure 5(a) shows the plate cross-section with the test points numbered 1 through 7. The spacing between points was 200 mm. Each test location indicates the position of the receiving transducer which in every case was located over the intersection of two bars. The impact point was located about 50 mm from the transducer. A mechanical impactor was used, and the contact time was approximately 40 microseconds.

Figure 5(b) shows the waveforms obtained at points 1 through 7. It is obvious that the waveform for point 6 contains closely-spaced oscillations which are not present in the other waveforms. The close spacing of the oscillations indicates that a flaw is located close to the surface. Similarly, the waveforms for points 2 and 3 also exhibit more close-spaced perturbations than the other waveforms, indicating that a flaw is present. If time domain analysis were used, each of these waveforms would have to be analyzed to determine wave arrival times [2]. However, as has been shown, frequency analysis is much simpler and quicker.

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[1]The highest frequency of components having significant amplitude is approximately the inverse of the contact time.

Figure 5(c) shows the spectra obtained from the waveforms in Fig. 5(b). Notice first that all spectra contain a high amplitude peak at or near 3.91 kHz which is the P-wave thickness frequency. However, the spectrum for point 3 contains an additional peak at 7.81 kHz and the spectrum for point 6 contains an additional peak at 15.9 kHz. Using Eq. (3) and the P-wave speed in this plate, these frequency values give calculated flaw depths of 260 and 126 mm, respectively, which agree with the known depths of the flaws. Notice that the spectrum for point 2 also contains additional peaks near 8 kHz, even though the test point is not located over the 260-mm deep flaw. This is because point 2 is located close enough to the flaw to be affected by waves diffracted from the edge of the flaw [1,3]. In a systematic scan, such as carried out in this example, it is generally easy to determine the approximate extent of a flaw. Spectra obtained near the edges of a flaw (point 2) show a scatter of peaks near the frequency corresponding to the flaw depth, while spectra obtained directly over a flaw (points 3 and 6) exhibit a single, large amplitude peak at the frequency corresponding to the flaw depth. A more subtle indication of the presence of a flaw is the shift of the value of the P-wave thickness frequency peak to a slightly lower frequency when the test point is located directly over a flaw. Notice that in the spectra for points 3 and 6 the low frequency peak is at 3.42 kHz instead of at 3.91 kHz as obtained over the solid portions of the plate. This shift occurs because the waves must travel around a flaw before being reflected at the plate bottom. The travel path of the waves increases, and thus the frequency of wave arrivals is slightly less.

Simulated Crack

Figure 6 shows results obtained from a series of tests along a section of the plate containing a 0.075-mm thick plastic sheet (300 mm x 1 m in plan) which was used to simulate a crack. The plastic sheet was placed in the fresh concrete at a depth of approximately 300 mm during casting of the plate. Figure 6(a) shows the cross-section containing the plastic sheet and the series of test points which were numbered 1 through 9. Spacing between points was 100 mm. In this case, the transducer was located over the intersection of two reinforcing bars for odd numbered tests and directly over a single bar for even numbered tests. The impact point was located a distance of 50 mm from the transducer. A mechanical impactor was used, and the contact time was approximately 80 microseconds.

Figure 6(b) shows the waveforms obtained from this series of tests. In this case, the presence of the flaw is much more difficult to detect than in the series of waveforms shown in Fig. 5(b) for two reasons: (1) The planar disk-shaped flaws made of rigid foam act as air voids producing strong reflections because nearly 100 percent reflection occurs at a solid/air interface. In contrast, the plastic sheet allows stress transfer across the simulated crack; thus reflections produced by the simulated crack are weaker. (2) The contact time of the impact was twice as long;

in waveforms generated by longer duration impacts, displacements caused by each wave overlap and the response becomes smoother [3,4]. A close look at Fig. 6(b) shows that there are perturbations (identified by arrows) in the waveforms for points 6, 7, and 8 which are not present in the other waveforms. However, it would be difficult to determine the depth of the flaw from these waveforms.

In contrast, a look at the spectra in Fig. 6(c) quickly reveals the presence and depth of the flaw. Spectra 6, 7, and 8 each contain a peak at 7.81 kHz produced by P-wave reflections from the surface of the simulated crack. The crack depth is calculated to be 260 mm. As in the previous case, all spectra contain the thickness frequency peak at 3.91 kHz produced by P-wave reflections between the top and bottom surfaces of the plate. However, this peak does not shift to a lower value over points 6, 7, and 8, which indicates that the waves travel directly across the simulated crack.

The interpretation of the results shown in Figs. 5 and 6 is typical of the authors' current approach to the analysis of test results. Time domain waveforms are used as indicators of the presence of flaws, while amplitude spectrum analysis is used to accurately determine the depth of flaws. The important point is that amplitude spectrum analysis is quick and generally simple; one does not need to be an expert in wave propagation to interpret the results.

Other Flaw Studies

Figures 5 and 6 showed responses obtained from only two of a variety of types of flaws contained in the 500-mm thick concrete plate. A detailed discussion of the results obtained from the other types of flaws in this plate is given in Chapter 7 of Reference [3]. Using frequency analysis, the authors were able to determine the depth of a vertical surface opening crack and the orientation and depth of flaws placed at angles to the surfaces of the plate. Also a hollow metal duct could be distinguished from a fully grouted duct. Although these studies were not comprehensive, the results showed the ability of the impact-echo to detect these types of flaws under laboratory conditions. The next step was to test the technique under field conditions. The following section describes the results of a study of an outdoor, ice-skating rink slab which was believed to contain voids.

FIELD STUDY

The impact-echo technique was used on a concrete slab (approximately 130 to 150-mm thick) which contained 16-mm diameter cooling pipes spaced 100 mm on center and located about 50 mm below the top surface of the slab. The slab also contained 13-mm diameter (No. 4) reinforcing bars placed 300 mm on center in both directions. The depths of the two layers of bars were approximately 53 and 66 mm. The slab was cast on a layer of rigid foam insulation. Portions of the slab were known to contain pockets of unconsolidated concrete below the cooling pipes. These pockets were believed to have lateral dimensions on the order of 50 to 100 mm. The objective of the study was to determine whether the impact-echo method could detect the presence of these small voids.

Preliminary Laboratory Study

Prior to conducting field tests, a laboratory study was performed in which a mock-up of the actual slab was built and tested. The mock-up was built so that experience could be gained using the impact-echo method to test a thin slab containing small voids. The 150-mm thick laboratory slab contained a 16-mm diameter pipe, 13-mm diameter reinforcing bars, and a small void below the pipe created from rigid foam insulation board. The depth of the void was 80 mm and the slab was cast on a 50-mm thick layer of foam insulation board. Figure 7(a) shows the cross-section of the laboratory slab.

A series of tests was performed at 25-mm intervals along the length of the pipe as shown in Fig. 7(b). At each test point, the impact point and receiving transducer were each located about 25 mm away from the centerline of the pipe so that they straddled the pipe. Because of the smaller slab thickness and flaw size as compared with previous studies, a shorter contact time was required. The impact source was a 5-mm diameter steel ball, and the contact time was approximately 20 microseconds. The P-wave speed in the specimen was determined to 3810 m/s.

Figure 8 shows the amplitude spectra obtained from waveforms recorded at points 16 through 25. (The void was located beneath test points 20 through 24.) In addition to frequency, the horizontal axis in Fig. 8 shows the depths corresponding to various frequency values for the P-wave speed of 3810 m/s (Eq. 3). The thickness frequency for the solid plate is 12.7 kHz, and a peak at this frequency is the dominant peak in the spectra obtained at points not located over the void (16 through 19). Note that the spectra for points 16 through 19 are similar; this is the pattern to be associated with the unflawed portion of the slab. The spectra obtained over the void (except for point 24) are distinctly different in two ways: (1) the thickness frequency peak is often split into a series of peaks; and (2) there are relatively large-amplitude peaks occurring between 20 and 40 kHz which are associated with waves reflected and diffracted from the top of the void. The spectra for points 20 through 23 are clearly different from those obtained over the unflawed portion of the slab. Thus it was concluded that the impact-echo technique should be capable of locating small voids (50 to 100 mm in size) beneath the cooling pipes in the actual slab.