Imaging Concrete Structures Using Air-Coupled Impact-Echo

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Abstract: In this paper, air-coupled impact-echo is successfully applied for nondestructive evaluation of concrete. The air-coupled sensor is a small (6.3 mm diameter) measurement microphone located several centimeters above the top surface of the concrete being evaluated. Unwanted ambient acoustic noise is attenuated by a specially designed sound insulation enclosure. Test results show that air-coupled sensors are effective for impact-echo when appropriate impactors are used. Impact-echo data obtained by air-coupled sensors are equivalent to those obtained by conventional contact sensors. Test results from concrete slabs containing artificial delaminations and voids are reported, where an air-coupled impact-echo scan is conducted over the entire slab area. Defects are located in the generated two-dimensional contour image. The areal size of defects are accurately determined when the measurement point spacing in the scan is smaller than half of the expected defect size. Test results from air-coupled impact-echo scans carried out over internal metal and plastic ducts within another concrete slab are also reported. The goal of the experiment is to investigate the grouting condition inside the ducts. Impact-echo line scan images differentiate poorly grouted sections from the well-grouted sections within the metal duct.

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Introduction

Problem Background and Significance

Corrosion-induced damage is one of the most serious problems affecting the service life of reinforced concrete structures. Concrete bridge deck deterioration is due primarily to corrosion-induced delamination (Bettigole and Robinson 1997). Recent structural failures in Europe have generated concern about post-tensioned concrete structures; voids within grouted tendon ducts, due to insufficient grout filling, significantly accelerate the corrosion of the embedded steel tendons (Martin et al. 2001). Nondestructive evaluation (NDE) techniques that can detect, locate, and characterize delamination and duct void defects in concrete are of great interest to infrastructure management agencies (Rens 1998).

Impact-Echo Method

Impact-echo has emerged as one of the most commonly used NDE methods for concrete defect detection since it was first proposed in the 1980s (Carino et al. 1986). It has been used to determine the location, extent, and depth of flaws such as cracks, delaminations, voids, honeycombing, and debonding in concrete structures (Sansalone and Streett 1997). Impact-echo is a mechanical wave-based NDE technique, where a transient point load (e.g., an impact event) is applied to the surface to generate waves in the concrete. The resulting transient surface motion, which is set up by a vibrational resonance through the thickness of the element, is detected by a sensor mounted on the surface. The obtained time domain signal is transformed to frequency domain (amplitude spectrum), where the frequency value at the maximum amplitude (peak) is monitored. The slab thickness (or depth to defects) $H$ is related to $P$-wave velocity $C_p$ and peak frequency $f$ of the frequency spectrum by

$$H = \beta C_p / 2f$$

where $\beta$ is approximately 0.96 for plate-like structures (Sansalone and Streett 1997). A recent study shows that the impact-echo resonance actually corresponds to the $S_1$ mode Lamb wave at the zero group velocity frequency condition (Gibson and Popovics 2005). When an internal air-filled defect lies below the impact-echo test location, the impact-echo resonance frequency is altered. The nature of the defect determines the extent to which the vibration resonance behavior changes. For example a flat defect that is parallel to the surface and having relatively large areal size will cause the impact-echo resonance frequency to increase as a function of the depth to that defect; the depth to defect can then be reliably measured using Eq. (1). If the defect is small, not flat, or not parallel to the surface, the resonance behavior is affected differently: The impact-echo resonance frequency decreases slightly since the defect acts to increase the mechanical compliance of the element at that location. Eq. (1) cannot be used to infer defect depth in this situation. Impact-echo, like many other mechanical wave-based NDE methods, is a contact, local point inspection method. Therefore, it can be time-consuming and labor-intensive to test large structures or pavements.

In the particular case when impact-echo is applied above a near-surface delamination defect, another resonance mode dominates the transient response and obscures the impact-echo resonance (Sansalone and Streett 1997). This vibration mode, referred to as the “flexural mode” in the early impact-echo literature (and in subsequent referral in this paper), represents the out-of-plane vibration of the thin section of concrete above a shallow delami-
nation. This vibration mode, which generates the hollow sounds heard when a chain is dragged across the surface of a delaminated slab, is analogous to the fundamental transverse vibration of a thin plate since the frequency is affected by the size, thickness, and shape of the thin section. The writers carried out an analytical investigation of impact-echo flexural frequency and determined that the response lies between those of the simply supported and clamped boundary conditions of classical thin plate vibration models. Thus neither Eq. (1) nor classic thin plate transverse vibration formulations are appropriate and should not be applied when such flexural modes are measured. Thus individual impact-echo data sometimes provide incomplete information about the type and depth of defects underlying the testing point.

When conventional (contact) impact-echo is used to investigate grouting condition of a tendon duct, downward frequency shift provides important evidence of the presence of a void (Sansalone and Streett 1997). Thorough analyses have been conducted by Abraham and Côte (2002) to study the effect of size and location of voids in tendon ducts on impact-echo frequency shift.

**Imaging**

Visual images that map the location, size, and shape of embedded damage or flaws provide a direct way for engineers to evaluate the condition of concrete structures. Many individual data are needed to construct a single image, however, and the inherent large size of concrete structures results in an enormous amount of data needed to construct an adequate image. Several NDE imaging techniques have been developed, for example, radiography with penetrating radiation, RADAR with electromagnetic pulsed waves, and infrared thermography (ACI 1998). However, these techniques have significant, inherent drawbacks that limit the ability to detect and image flaws within concrete structures. Radiographic techniques are limited by safety and cost issues and require access to opposite sides of the structure. Electromagnetic waves are affected by the dielectric properties, as opposed to mechanical properties, of the material and so are strongly reflected from embedded steel reinforcing bars, often masking the signals from underlying flaws. Also, electromagnetic waves are disturbed by varying moisture and salt contents within the concrete, thereby complicating the interpretation of RADAR images for flaw detection and identification. Thermography is efficient for detecting delaminations in large structures, but it is disrupted by weather and surface conditions and does not provide information about the depth of defects (Buyukozturk 1998). All these techniques require expensive equipment, and the test results are not directly related to the mechanical properties of materials.

On the other hand, mechanical wave-based test methods, such as impact-echo and ultrasound, enable inspection well below the surface of the concrete structure, offer direct information concerning the effective elastic constants, and are sensitive to the presence of damage and flaws. However, the use of mechanical wave data to create visual images is limited by the required physical contact and coupling of the transducers: Mechanical wave NDE techniques require good contact between the sensor and tested concrete surface to obtain reliable data. The necessary surface preparation is often very time- and labor-consuming due to rough surfaces or limited access of concrete structures. Sensor contact also introduces disturbing experimental variations, and significantly reduces efficiency of measurement (Buyukozturk 1998).

Nevertheless, developments in sonic/ultrasonic imaging of concrete structures have been reported (Rhazi et al. 1997; Schickert et al. 2003).

**Air-Coupled Sensing**

One solution for the problem of slow testing rate of mechanical wave methods is the application of contact-less sensing. By eliminating the contact between sensors and concrete surfaces, the possibility of an automated scanning system is enabled. Both lasers and air-coupled (acoustic) sensors can be used for contact-less mechanical wave detection in solids. However, the inherent rough surface of concrete limits laser application. Air-coupled ultrasonic sensing has undergone rapid development in recent decades, especially for guided wave detection in metals (Wright and Hutchins 1999), despite the huge (four orders of magnitude) acoustic impedance mismatch between solids and air. However, the inhomogeneous and variable nature of concrete limits the practical application of fully air-coupled (contact-less excitation and detection) ultrasonic methods (Cetrangolo and Popovics 2006; Berri man et al. 2005). The wave energy transmission is dramatically increased when a contact (e.g., impact) source is used with an air-coupled receiving sensor. Although this system is not fully contact-less, elimination of surface coupling for the receiving sensor reduces testing time and air-coupled sensors are reported to show improved signal consistency over contact sensors (Berri man et al. 2005). Efforts to use air-coupled acoustic sensors to inspect concrete date back to 1973, when the Texas Transportation Institute in College Station, Tex. developed an automated delamination detection device called Delamatec (Moore 1973; Moore et al. 1973). The essential components of Delamatec are automated tappers, a strip chart recorder, and acoustic receivers. When applied over sound (defect-free) concrete, the obtained time domain signal is flat and close to zero; the signal becomes irregular when over a delamination. However, application of the Delamatec has been limited owing to poor accuracy. More recently air-coupled sensing for surface waves in concrete structures was proposed by Zhu and Popovics (2001). The test results, which were verified by comprehensive theoretical analyses (Zhu et al. 2004), demonstrated that directional microphones are very sensitive to leaky surface waves propagating along concrete. Leaky surface waves exist at the boundary between a solid and fluid, and arise from the propagating mechanical surface waves in the solid: The resulting wave motion at a point on the surface of the solid generates acoustic waves that “leak” into the surrounding fluid (Viktorov 1967). Subsequent studies by Zhu (2005) and Ryden et al. (2006) have shown that air-coupled sensors can replace contact sensors in most surface wave measurement tests, e.g., SASW (spectral analysis of surface waves) and MASW (multi-channel analysis of surface waves). Further, air-coupled surface wave sensing can also be applied to locate surface cracks in concrete slabs (Zhu and Popovics 2005).
Impact-echo is known to be effective for detection of important defects in concrete. However, the application of air-coupled sensing for impact-echo is more challenging than for surface waves. This paper presents an effort to develop an air-coupled impact-echo testing setup. Air-coupled impact-echo scanning tests were carried out over two concrete slabs that contain embedded artificial defects. Test results, shown as images, identify locations and areal size of most of the defects.

**Testing Setup and Equipment**

Equipment and procedures for air-coupled impact-echo tests are described here. The approach extends the concept of the Delamatec system by incorporating the following improvements: The air-coupled sensor measures waves across a broader frequency range, the signals of air-coupled impact-echo are analyzed in the frequency domain instead of the time domain, and more detailed analysis is enabled by applying the impact-echo formulation. Further, the development in hardware and computer imaging techniques enables the creation of images that allow more effective interpretation of the test data for characterization of concrete structures.

**Testing Setup**

The testing setup of air-coupled impact-echo is shown in Fig. 1. The configuration is similar to conventional impact-echo except there is no contact between the sensor and the test surface. The sensor is located nearby the impact location; the distance between the sensor axial projection point on the surface and the impact point \( x \) is less than 40% of the slab thickness. In air-coupled (leaky) surface wave detection (Zhu et al. 2004; Zhu and Popovics 2005), direct acoustic waves do not disrupt the time signal as the acoustic waves can be isolated by increasing the source–receiver spacing \( x \). Further, the leaky surface wave pulse is isolated and extracted by applying a Hanning window to the time signal. However in the impact-echo testing scheme the sensor is located nearby the impact location. The impact source causes much acoustic noise in the received signals, which cannot be isolated in the time domain and removed because of the relatively small source–receiver spacing in the impact-echo test setup.

**Fig. 2.** Design of sound insulation enclosure for the air-coupled sensor

**Fig. 3.** Signals showing the insulating effect of microphone enclosure. (a) Signals recorded by the microphone without insulation; (b) signals with insulation, where the total response includes contributions from impact-echo vibration and direct acoustic waves.
Further, the entire time signal is needed to set up the impact-echo resonance behavior needed for the analysis. To obtain reliable and consistent results with air-coupled impact-echo, the direct acoustic waves must therefore be suppressed. To overcome this difficulty, adequate sound insulation is required to reduce the energy of acoustic waves detected by the sensor, and the impactor must excite impact-echo resonances in concrete without generating excessive acoustic noise.

Air-Coupled Sensors

A measurement microphone manufactured by PCB Inc. was used in the air-coupled impact-echo tests. It has a small size (6.3 mm diameter), broad frequency range (4–80 kHz at ±2 dB), and high sensitivity (4 mV/Pa). This sensor is well suited for impact-echo scanning as it is able to detect a broad range of frequencies and its small size enables improved spatial resolution in scanning tests.

A special enclosure was designed to support the microphone; it also provides sound insulation to shield ambient noise and direct acoustic waves. Fig. 2 shows a drawing of the microphone and the insulation enclosure. The enclosure wall has an inner layer of rubber, an aluminum cylinder, and an outer foam layer. The foam and aluminum work together to absorb and/or reflect most ambient noise and direct acoustic waves, whereas the inner rubber layer absorbs the leaky waves from the concrete surface and suppresses the formation of resonances within the cylindrical enclosure cavity. The microphone is inserted into the enclosure through a hole. The microphone height can be easily adjusted. Experimental studies were carried out to investigate the sound insulating efficiency of the enclosure. The tests were carried out on two identical concrete slabs that were placed next to each other, but fully isolated. To measure the total response (impact-echo plus direct acoustic wave), the impact was applied to one slab and the sensor monitored that same slab at a fixed spacing configuration. To isolate the direct acoustic wave from the total response, the impact was applied to one slab, but the adjacent slab was sensed using the same spacing configuration. As shown in Fig. 3, this enclosure design reduced the amplitude of direct acoustic waves by 40% (from 50 to 10%), with respect to the total response.

Fig. 4. Slab 1 containing ducts and a notch. (a) Plan view; (b) Cross Section A-A. Location of all intentional defects are marked. Dashed lines indicate cross-duct scan paths. All dimensions in millimeters.
amplitude. Fig. 3(a) shows the signals without insulation, in which the direct acoustic wave/total response amplitude ratio is 1:2; whereas in Fig. 3(b), the ratio is 1:10 (0.1–1.0 V). Ambient noise amplitudes were also significantly reduced.

**Impactors**
A set of wire-mounted solid steel balls ranging in diameter from 5 mm (0.5 g) to 15 mm (14 g) are used as impact sources. These impactors allow effective excitation of impact-echo resonance in concrete without generating excessive acoustic noise. As with conventional contact impact-echo, selection of proper ball size is critical for detecting defects at different depths as the ball size controls the range of frequencies that are excited; ball diameter is inversely related to the maximum frequency that can be excited efficiently (Sansalone and Streett 1997).

**Data Acquisition and Signal Processing**
The slab vibrations set up by the impact source are detected by the microphone and the signal is then digitized by a digital oscilloscope. Each transient signal is collected for duration of 4 ms with a sampling interval of 1 μs. A signal conditioner is needed to amplify the microphone output. A Labwindows (National Instruments, Austin, Tex.) program was developed to facilitate signal acquisition and analysis.

**Concrete Specimens Containing Artificial Defects**
Two steel-reinforced concrete slabs were cast from a single batch of concrete. The slabs are nominally 0.25 m thick with 1.5 by 2.0 m lateral dimensions. The 28 day compressive strength of the concrete is 42.3 MPa. P-wave velocity of the mature concrete, determined by ultrasonic pulse velocity measurement (ASTM 1997), is 4,100–4,200 m/s. This results in a nominal full-thickness impact-echo frequency of 7.81–8.06 kHz [Eq. (1)].

Slab 1 contains two continuous embedded ducts: one plastic (wall thickness=5 mm) and one metal (wall thickness=1 mm). Each duct is divided into three sections: fully grouted, half-grouted, and ungrouted. The voids in the half-grouted and ungrouted regions are simulated by foam inserts. The diameters of both ducts are 70 mm, and the centerlines of the ducts are 125 mm below the surface. The same specimen also contains a surface-opening notch with linearly increasing depth. The study of nondestructive evaluation of crack depth is reported elsewhere. The plan view and cross section of the slab are shown in Fig. 4.

Slab 2 contains artificial delaminations and voids of varying size and depth. The plan view and cross section of the slab are shown in Fig. 5. Since the loading capacity of the slab is significantly reduced by the artificial defects, the slabs are reinforced in two dimensions and at two layers. The top layer of steel bars is supported by five steel chairs. The concrete cover thick-
ness is 60 mm. Metal wire mesh (150 by 150 mm) was placed above each rebar layer. Artificial delaminations were simulated by embedding six double-layer plastic sheets. Three double-layer sheets are located 60 mm below the surface (top sheets), and three 200 mm below the top surface (bottom sheets). The actual depths of the sheets were measured in the slab form before casting concrete and are shown in Table 1. Internal voids were simulated by embedding 300 and 100 mm diameter soft foam blocks. The plastic sheets and foam blocks were secured to the wire mesh with tie wire. The photo in Fig. 6 shows the location of defects and rebar layout.

### Effect of Source-to-Receiver Spacing

The effect of source-to-receiver spacing \(x\) on air-coupled impact-echo was investigated. The microphone was positioned 3 cm above a solid (defect-free) portion of the 250 mm thick concrete slab; the source–receiver spacing \(x\) varies from 3 to 30 cm. Test results shown in Fig. 7 confirm that the correct impact-echo frequency is obtained when \(x\) is within the range of 5–22 cm. However, for \(x > 22\) cm, which is close to the slab thickness, the signal spectrum is not necessarily dominated by the impact-echo frequency; instead other resonant modes may dominate the spectrum. Without prior knowledge of the slab properties, it is difficult to distinguish the correct impact-echo frequency. Gibson and Popovics (2005) show that the impact-echo resonance frequency in a plate or a slab corresponds to the zero group velocity condition of the \(S_1\) mode of Lamb waves. By this theory, impact-echo frequency should not change with source–receiver spacing. However, the excitability of the \(S_1\) mode decreases dramatically as source–receiver spacing increases. Gibson’s analysis (Gibson 2005) shows that for \(x = 1.0H\), where \(H=\) slab thickness, the \(S_1\) mode excitability decreases by 85% compared to \(x = 0.3H\). For air-coupled impact-echo test, the disrupting effects of ambient noise and direct acoustic waves become significant when the \(S_1\) mode excitability is low. Therefore, as in the contact impact-echo test, care should be taken to choose proper source–receiver spacing for air-coupled impact-echo. Further, smaller spacing gives better spatial resolution for impact-echo imaging. In these tests, the source-to-receiver spacing was confined to within 20 cm.

### Air-Coupled Impact-Echo for Delamination Detection

#### Point Test Results

Individual air-coupled impact-echo tests were carried out over solid (defect-free) and all defect regions on Slab 2. The objective here is to show that contact and air-coupled impact-echo results are effectively equivalent. The nine defects are numbered 1 to 9 from the left top corner to the right bottom corner (Fig. 5). The sensor was positioned over the center of each defect in the case where defect regions were tested. The lateral source-to-receiver spacing \(x\) is between 5 and 10 cm, and the sensor was 3 cm above the concrete surface.

The air-coupled impact-echo results are shown in Table 1. The test locations are grouped according to type of defects. For example, Test Locations 1, 3, 6, and 8 are over shallow delamination about 55 mm below the top surface. There is no known defect at Point 0, where the full thickness frequency 7.81 kHz

### Table 1. Air-Coupled Impact-Echo Results Obtained from Test Slab 2

<table>
<thead>
<tr>
<th>Test point</th>
<th>Defect size (mm)</th>
<th>Dominant frequency (kHz)</th>
<th>Tested thickness (mm)</th>
<th>Measured thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (solid)</td>
<td></td>
<td>7.81</td>
<td>252</td>
<td>250</td>
</tr>
<tr>
<td>1 (shallow)</td>
<td>200x200</td>
<td>4.15</td>
<td>Flexural mode</td>
<td>55</td>
</tr>
<tr>
<td>3 delam</td>
<td>100x100</td>
<td>7.44</td>
<td>Flexural mode</td>
<td>55</td>
</tr>
<tr>
<td>6</td>
<td>400x600</td>
<td>1.22</td>
<td>Flexural mode</td>
<td>55</td>
</tr>
<tr>
<td>8</td>
<td>300x300</td>
<td>2.69</td>
<td>Flexural mode</td>
<td>55</td>
</tr>
<tr>
<td>4 (voids)</td>
<td>Diameter 300</td>
<td>2.93</td>
<td>Flexural mode</td>
<td>75</td>
</tr>
<tr>
<td>5</td>
<td>Diameter 100</td>
<td>7.09</td>
<td>Flexural mode</td>
<td>60</td>
</tr>
<tr>
<td>2 (deep)</td>
<td>300x300</td>
<td>10.62</td>
<td>185</td>
<td>190</td>
</tr>
<tr>
<td>7 delam</td>
<td>200x200</td>
<td>10.62</td>
<td>185</td>
<td>195</td>
</tr>
<tr>
<td>9</td>
<td>100x100</td>
<td>7.69</td>
<td>—</td>
<td>190</td>
</tr>
</tbody>
</table>

![Fig. 6. Photo of the form for Slab 2 (before casting) containing artificial delaminations and voids](image)
was obtained. For shallow delaminations, the peak frequencies of air-coupled impact-echo tests are significantly lower than the full thickness frequency. In these cases, the peak frequencies do not correspond to the impact-echo resonance mode, but are set up by a flexural vibration resonance mode. As with conventional contact impact-echo, flexural mode frequencies are affected by depth, areal size, and edge support conditions of defects (Sansalone and Streett 1997). With similar depth and support conditions, larger defect areas result in lower frequencies. The results show that shallow delaminations are easy to detect with air-coupled impact-echo: The peak frequencies shift lower in the frequency spectra. The void regions (Points 4 and 5) behave like shallow delaminations, since the top surfaces of the voids are only 75 and 60 mm below the surface; thus low frequency flexural modes are set up.

Flexural mode frequency measurement is more consistent and less affected by ambient noise than that of the impact-echo resonance mode. The flexural mode frequency measured by the air-coupled sensor without the sound insulation enclosure agrees with the result measured by a conventional contact sensor. This result verifies the research of Asano et al. (2003): The emitted impact sound (direct acoustic waves) frequency matches the flexural mode frequency. This principle explains why conventional sounding methods (e.g., chain drag) are effective for identifying the presence of large areas of near-surface delamination in concrete decks.

Test Points 2, 7, and 9 are over deep delaminations at depth of 190–195 mm below the surface. The obtained impact-echo peak frequency at 10.62 kHz for Points 2 and 7 give thicknesses of 185 mm [Eq. (1)], which agree well with the actual depth of 190 mm. However, accurate depth information was not obtained at Point 9, because the defect is too small and deep. The obtained peak frequency slightly shifts lower in frequency, which indicates possible presence of defects.

Since the signals over shallow delaminations are dominated by flexural vibration, the depth of delamination cannot be inferred directly from the dominant peak frequency. According to the conventional impact-echo equation [Eq. (1)], the impact-echo mode frequency should be high for shallow delaminations. Therefore, broader frequency contents must be investigated if depth information is to be obtained. Figs. 8(a and b) show impact-echo signals obtained from the air-coupled sensor over a shallow delamination (Defect 8). In the frequency spectrum, a clear peak at 33.2 kHz is seen in addition to that at 2.68 kHz, which corresponds to the flexural mode. The high frequency peak is caused by the impact-echo mode resonance: Eq. (1) gives an estimated delamination depth of 59 mm, which agrees well with the actual depth of 55 mm. To excite such high frequencies, a very small ball (5 mm diameter) impactor must be used, as the maximum excited frequency is inversely related to increasing ball size (Sansalone and Streett 1997). The 33.2 kHz peak frequency, however, is difficult to detect with a standard contact impact-echo sensor even when a small impactor is used, as seen in Figs. 8(c and d). The contact sensor measures vertical (out-of-plane) displacement at the concrete surface. The air-coupled sensor measures air pressure, which is equivalent to out-of-plane velocity at the surface (Zhu et al. 2004). Displacement sensors are less sensitive to higher frequency content than velocity sensors. Velocity responses show satisfactory sensitivity across a broader (higher) range of frequency.

Two-Dimensional Imaging

A two-dimensional (2D) scanning test was carried out over the entire area of Slab 2 (200 by 150 cm). The measurement grid spacing is \( \Delta x = \Delta y = 10 \text{ cm} \) in both directions; therefore in total \( 19 \times 14 = 261 \) signals were obtained. (No data were collected along the slab edges.) However, the contact-less property of the sensor allowed efficient scanning of the specimen, with a testing...
Fig. 9. (Color) Two-dimensional contour images of Slab 2 built up using air-coupled impact-echo data. The solid lines indicate location of defects.

Fig. 10. (Color) Two-dimensional contour images of Defects (a) 1; (b) 7; and (c) 9 in Slab 2. Defect 1 is a shallow delamination at depth of 55 mm, and Defects 7 and 9 are deep delaminations at depth of 190 mm. A finer color scale range is used for (c) to improve image contrast.
time of approximately 10 s per point. The testing efficiency would be further improved if an array of sensors were employed. Data were collected along parallel scan lines. A 2D matrix composed of the frequency of a signal’s amplitude spectrum at the highest amplitude (peak frequency) for each testing location is used for image construction. Fig. 9 shows the 2D scan contour image of Slab 2. The image was created using the “contour” plotting function in MATLAB. In the color image, warm colors represent high frequencies, and cold colors low frequencies. The designed defect locations and areal size are also indicated on the image with solid lines.

Most of the defects are identified in the image. For large and shallow delaminations and voids, i.e., Defects 1, 4, 6, and 8, the approximate areal size of damage regions is determined, and agree well with the actual areal size. For the small defects, i.e., Defects 3, 5, and 9, the image shows frequencies that are slightly lower than the normal full-thickness frequency; this indicates the possible presence of small defects. Although the size and depth of the small defects cannot be accurately determined, they can still be differentiated from the surrounding solid regions. Hot spots (high frequency) are observed over Defect 2 and 7, which indicate the existence of deep delaminations. However, the areal size of the defects cannot be accurately determined; the high frequency corresponding to the impact-echo resonance set up by deep delamination is observed only within a small region near the center of damaged area. The peak frequency shifts to a lower frequency when the test point is located over edges of the defect.

In addition to the nine designed defects, regions marked “A” and “B” in Fig. 9 show warmer colors from the surrounding solid regions. These regions exhibit slightly higher frequency than the full-thickness frequency at 7.8 kHz even though there are no known or intended defects in these regions. Close examination of the photo in Fig. 6 reveals two steel chairs at Locations A and B, which were used to support the top layer rebars. Since the concrete in the slab was obtained from a single batch source, and thus the material properties (wave velocities) are likely very consistent throughout, we conclude that the vertically positioned steel chairs act to stiffen the cross section of the slab at these locations resulting in a slightly higher impact-echo resonance frequency.

**Refined Scans**

Refined 2D scans were conducted over Defects 1 (shallow delamination), 7, and 9 (deep delamination), using a 5 cm scan spacing. The imaged regions for Defects 1 and 7 are 40 by 40 cm squares, and for Defect 9 a 25 by 20 cm rectangle. The scan
images are shown in Fig. 10. The refined scans provide improved definition of defect size, especially for the shallow delamination (Defect 1). In Fig. 10(a), a clear boundary is observed between the delaminated and solid regions. The lowest flexural mode frequency is obtained over most of the central region over the defect, and the frequency increases as the test point moves close to edges of the defect.

For Defect 7, defect area definition is less clear in the image. High frequencies are observed in the center of the defect. The frequency gradually and continuously reduces as the test point moves close to edges of the defect, whereas lower frequencies are observed near the defect edges. Low frequency (lower than the full thickness frequency 7.8 kHz) is observed over the edges of the defect. The impact-echo mode is readily excited over the center of defects, while multiple modes are excited near the defect edges. These edge modes have lower frequencies than the full-thickness impact-echo frequency due to reduced slab stiffness. The depth of delamination can still be estimated accurately from the peak frequency at the defect center. The additional utility of evaluating multiple point data together in a single image is thus illustrated: The center region of a deep delamination defect can more reliably be determined as compared to evaluating the same point data individually as is done in conventional impact-echo. Defect 9 is small and deep, therefore the impact-echo resonance mode is difficult to excite as the point test should be carried out at the precise center of the defect. Existence of the defect, however, does reduce the stiffness of this region, and the peak frequency shifts to a lower value.

The refined scan shows improved spatial resolution to locate smaller defects in concrete. The results indicate that the scan spacing should be less than half the size of the defect to be imaged. In practice, 2 cm spacing is sufficient to generate a scan image with spatial resolution that meets most requirements. Such a fine spacing will generally produce large amounts of data and increased scanning time. However, air-coupled impact-echo enables the development of automated testing and scanning systems that can address these restrictions.

**Air-Coupled Impact-Echo for Characterizing Grouted Tendon Ducts**

Air-coupled impact-echo tests were carried out over Slab 1 to examine the grouting quality of the ducts. Line scans were first
conducted above and along the centerline of the ducts to investigate the ability to differentiate grouted from ungrouted ducts. The scan line starts at the ungrouted end and moves to the fully filled end. Cross-duct line scans were also carried out. The spacing between measurement points along the scan line is 5 cm.

Figs. 11 and 12 show the air-coupled impact-echo line scan images along the metal and plastic ducts, respectively. At each test point along the ducts, the impact-echo frequency amplitude spectrum is plotted in gray scale, where dark color indicates high amplitude and light color low amplitude. A line scan image is then constructed by stacking the spectra from all test points along the ducts; this image configuration is also known as a “B-scan.” To improve contrast of the image, the amplitude spectra data are raised to the fourth power.

For both ducts, $Y=0–50$ cm section is ungrouted, $Y=50–100$ cm is half-grouted, and $Y=100–150$ cm is fully grouted. The image in Fig. 11 shows clear distinction between the fully grouted section and the remaining sections of the metal duct. The fully grouted section shows on average 15% higher frequency than the ungrouted and half-grouted sections. Further, the

![Fig. 13. Air-coupled impact-echo line scans across the duct direction. The three images represent scans along three paths with different grouting conditions: (a) ungrouted; (b) half-grouted; and (c) fully grouted. X is the scan distance.](image)

![Fig. 14. 1.5 GHz GPR B-scan line images along cross-duct scan paths: (a) ungrouted; (b) half-grouted; and (c) fully grouted. Scan distance indicated along top of images in centimeters.](image)
frequencies from the fully grouted section are always above 7 kHz and those from the other sections always below 7 kHz. The higher frequency connotes higher slab stiffness in the fully grouted section (Sansalone and Streett 1997). Although there are some differences between the ungrouted and half-grouted sections, it is difficult to differentiate them because the difference in frequency is small.

The line scan results from the plastic duct are shown in Fig. 12. The grouting condition within the duct cannot be determined conclusively from the line scan image. The same limitation also applies to conventional contact impact-echo. The geometry of the duct itself likely causes this behavior. The thick-walled plastic duct is much more rigid than the thin-walled metal duct. Thus the grouting condition within the duct has relatively little contribution to the overall stiffness of the slab in the duct regions. Therefore the impact-echo scans cannot conclusively differentiate sections with different grouting conditions within rigid ducts.

Cross-duct line scans were conducted along three paths in the direction normal to the centerline of ducts. The three paths pass the midpoint of each defined section, as shown in Fig. 4. Fig. 13 shows three line scan (B-scan) images obtained from the different paths using air-coupled impact-echo. The plastic and metal ducts are located at x=20 cm and x=75 cm, respectively. At duct locations, the peaks of the amplitude spectra shift to lower frequency range as expected. It can be seen the duct locations are identified on the images, even in the fully filled sections. Although the peak frequencies from the ungrouted and half-grouted duct sections appear lower than that at the fully grouted section, it is difficult to differentiate the type of duct and the internal grouting condition.

Fig. 14 shows 1.5 GHz short-pulse RAdAR (GPR) B-scan line images along the same ungrouted, half-grouted, and fully grouted duct paths. The parabolic arches in the images represent typical electromagnetic wave reflections from the ducts: the plastic duct on the left and metal duct on the right. For the plastic duct, the arch-shaped reflections exist over the ungrouted and half-grouted sections, but disappear over the fully grouted section. GPR is effective in identifying fully grouted conditions in plastic ducts. The metal ducts cause strong reflection in all cases. The strong reflection by the duct itself causes a “masking” effect that prevents detection of voids within the duct. Impact-echo behaves in a different but complementary manner. Therefore, the combination of GPR and impact-echo would help improve the accuracy of duct characterization.

Conclusions

The following conclusions are drawn based on the work presented in this paper:

1. Air-coupled sensing offers an approach for effective evaluation of concrete structures through imaging. Multiple point data that are presented together in an image provide more diagnostic information than the same data evaluated individually.

2. Individual air-coupled impact-echo signals (amplitude spectra) are equivalent to those obtained from conventional contact impact-echo sensors, and the same analysis and interpretation procedures can be applied to both.

3. Air-coupled sensors with broad frequency response can provide more information about the dynamic response of slabs that contain shallow delaminations, as both the impact-echo and flexural vibration responses from the delamination are sensed.

4. Finer scan point spacing enhances the ability to define defect areal size in the created 2D image; scan point spacing should be less than half the areal size of a defect to accurately define it in the image. A 2 cm scan spacing should be sufficient to define all significant defects in a concrete structure.

5. In 2D impact-echo scan images, flexural resonances from shallow delaminations allow accurate definition of defect areal size. The depth of shallow delaminations cannot be determined directly from the flexural resonance frequency. The areal size of deeper defects, which are set up by impact-echo resonance, cannot be determined precisely although a boundary of low frequencies around high can provide some guidance to size. The depth of deep defects can be determined directly from the impact-echo resonance frequency when measured above the center of the defect.

6. Impact-echo line scans along the axis of an internal duct can provide comparative information about the grout filling condition of thin-walled (compliant) metal ducts; fully-grouted sections can be identified and differentiated from partially filled and empty sections. The filling condition of thick-walled (rigid) plastic ducts cannot be determined from the impact-echo line scans.

7. Scanning impact-echo complements other NDE line imaging techniques, such as GPR, likely providing more complete characterization of the duct condition when used together.

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Notation

The following symbols are used in this paper:

\[ C_p \] = P wave velocity in concrete;
\[ f \] = frequency;
\[ H \] = slab thickness or depth of defects;
\[ x \] = source to receiver spacing
\[ x, y \] = coordinates used in 2D scan;
\[ Y \] = location along the embedded ducts;
\[ \beta \] = correction factor for impact-echo test; and
\[ \Delta x, \Delta y \] = grid spacing of 2D scan.

References


