

# AIR-COUPLED IMPACT-ECHO IMAGING OF CONCRETE DECKS AND SLABS

John S. Popovics<sup>1</sup> and Jinying Zhu<sup>2</sup>

<sup>1</sup>The University of Illinois at Urbana-Champaign, johnpop@uiuc.edu

<sup>2</sup>CTL Group, jyzhu2@gmail.com

## ABSTRACT

In this paper, work on air-coupled impact-echo is described. The method is applied to locate and to determine the depth of simulated delamination and void defects in a concrete slab. A small (6mm diameter) measurement microphone is used to sense impact-echo response without contacting the surface of the concrete. Ambient acoustic noise effects are significantly reduced by a specially-designed sound insulation device. Test results show that air-coupled sensors work as effectively as do contact impact-echo sensors when proper impactors are used. An air-coupled impact-echo scan was conducted over the entire slab area, and the defects are located in a generated 2-D contour image. Experiments show that the areal size of near-surface delamination defects can be accurately determined if the scan spacing is smaller than 1/2 of the expected defect size. The study presented in this paper shows air-coupled sensing offers an approach for rapid and effective evaluation of concrete deck structures through imaging.

## INTRODUCTION

Non-destructive evaluation (NDE) techniques that can detect, localize and characterize damage and flaws in the infrastructure are of great interest. Impact-echo has emerged as one of the most commonly used NDE methods for concrete defect detection since it was first proposed in the 1980's (Carino et al. 1986). It can be used to determine the location and extent of flaws such as cracks, delaminations, voids, honeycombing, and debonding in concrete structures. Impact-echo is especially effective for locating and estimating depth of delaminations (Sansalone and Street 1997). Impact-echo is a mechanical wave-based NDE technique, where a steel ball applies a transient point load (e.g. an impact event) on 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  $f$  by

$$H = \beta C_p / 2f \quad (1)$$

where  $\beta$  is approximately 0.96 for plate-like structures. 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. In the particular case when impact-echo is applied above a near-surface delamination defect, another resonance mode (the fundamental flexural mode) dominates the transient response and obscures the impact-echo resonance (Sansalone and Streett 1997). Equation (1) is not appropriate and should not be applied when flexural modes are measured. Impact-echo, like many other mechanical wave based NDE methods, is a local point inspection method. Therefore, it can be time consuming and labor intensive to test large structures or pavements.

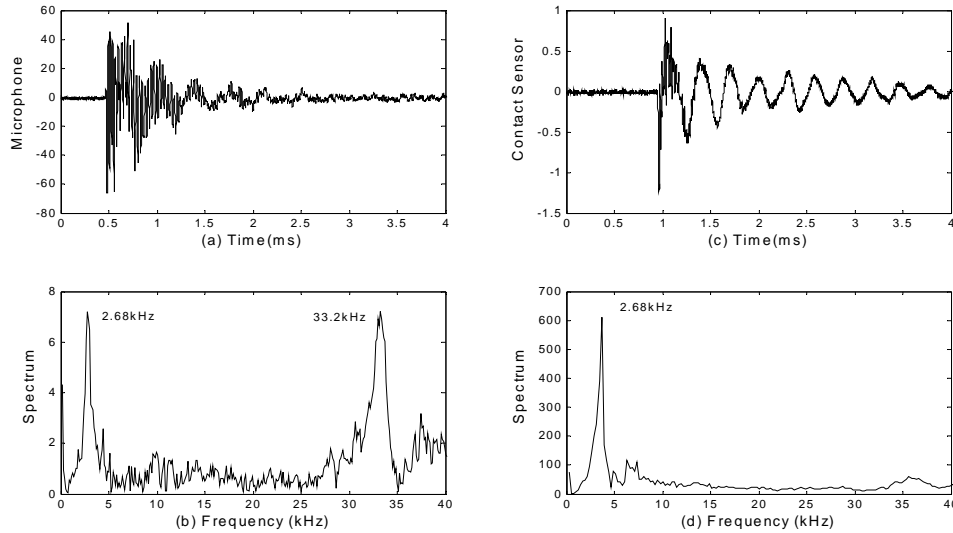
Visual images that map the location, size and shape of embedded damage or flaws provide a direct way for engineers to evaluate the condition of concrete structures. Many individual data are needed to construct a single image, however, and the inherent large size of concrete structures results in an enormous amount of data needed to construct an adequate image. 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. 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. Recently air-coupled sensing for surface waves in concrete structures was proposed by Zhu and Popovics (2001). 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). Furthermore, air-coupled surface wave sensing can also be applied to locate surface cracks in concrete slabs (Zhu and Popovics 2005).

### **TESTING CONFIGURATION**

The testing setup of air-coupled impact-echo 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's axial projection point on the surface and the impact point is less than 40% of the slab thickness. 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. 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.

The sensor used in the air-coupled impact-echo tests is a measurement microphone manufactured by PCB Inc. It has a small size (6.3 mm diameter), broad frequency range (4-80 kHz at  $\pm 2$ dB), and high sensitivity (4 mV/Pa). A special enclosure was designed to support the microphone; it also provides sound insulation to shield ambient noise and direct acoustic waves. A set of wire-mounted steel balls is used as impact sources. These impactors allow effective excitation of impact-echo resonance in concrete without generating excessive acoustic noise. 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  $\mu$ s. A Labwindows® program was developed to facilitate signal acquisition and analysis.

Figure 1 shows typical signals obtained using the air coupled sensor, as compared to those collected with a conventional contact sensor. The signals were collected from a concrete slab that contains a shallow delamination (60mm depth) defect. Both sensors indicate the delamination flexural mode at 2.83 kHz, but only the air-coupled sensor detects the high frequency impact-echo mode at 33.2 kHz. Thus the air-coupled sensor is function, and in fact is superior to the contact sensor in this case.



*Fig 1. Time domain signals (a) and (c) and associated frequency spectra (b) and (d) collected over a shallow delamination defect in concrete using an air-coupled sensor (left) and a conventional contact sensor (right).*

## TEST SPECIMENS

Two steel-reinforced concrete slabs were cast. The slabs are nominally 0.25m thick with 1.5 m by 2.0 m lateral dimensions. Slab No.1 contains two continuous embedded ducts: one plastic (wall thickness = 5mm) 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 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.

Slab No.2 contains artificial delaminations and voids of varying size and depth. 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 thickness 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. Internal voids were simulated by embedding 300 mm and 100 mm diameter soft foam blocks. The plastic sheets and foam blocks were secured to the wire mesh with tie wire.

The P-wave velocity measured by UPV test is 4100 m/s, which results in a nominal full-thickness impact-echo frequency of 7.81 kHz, according to Eq.(1).

## EXPERIMENTAL RESULTS

### Delamination Detection

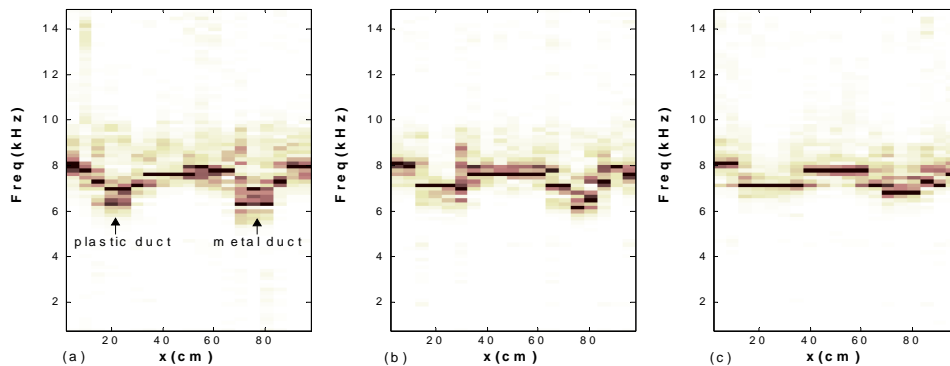
A 2-D scanning test was carried out over the entire area of slab No.2 (200 cm by 150 cm). The measurement grid spacing is  $\Delta x = \Delta y = 10\text{ cm}$  in both directions; therefore in total  $19 \times 14 = 261$  signals were obtained. (No data were collected along the slab edges.) The contact-less property of the sensor allowed efficient scanning of the specimen. Data were collected along parallel scan lines. A 2-D matrix composed of the peak frequency of a signal's amplitude spectrum for each testing location is used for image construction. The locations and areal size of most of the defects are identified in the image. For large and shallow delaminations and voids, the approximate areal size of damage regions are determined, and agree well with the actual areal size. In this case, the peak frequencies are significantly lower than the full-thickness impact-echo frequency 7.81 kHz. The vibrations are dominated by low frequency flexural resonant modes. For the small defects, 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. White spots (high frequency) are observed over two defects, which indicate 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.

### Duct Void Detection

Air-coupled impact-echo tests were carried out over slab No.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. The spacing between measurement points along the scan line is 5 cm.

Figures 2 shows the air-coupled impact-echo line scan image across the plastic and metal ducts along three different scan lines, across ungrouted, partially-grouted and fully grouted conditions respectively. At each test point along the duct, 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 4th power.



*Fig. 2 Air-coupled impact-echo scans across the centerlines of the plastic and metal ducts: (a) ungrouted section, (b) half-grouted section and (c) fully grouted sections.*

At metal duct locations, the peaks of the amplitude spectra shift to lower frequency range as expected. The duct locations can be 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. The images show distinction between the fully-grouted section and the remaining sections of the metal duct. The fully-grouted sections show higher frequency than the ungrouted and half-grouted sections, which indicates 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 grouting condition within the plastic duct cannot be determined conclusively from the line scan image. The same limitation also applies to the conventional contact impact-echo test. 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.

## SUMMARY

Air-coupled sensing offers an approach for rapid and 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. In 2-D 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. Impact-echo line scans along the axis of an internal duct can provide comparative information about the grout filling condition of thin-walled (compliant) ducts; fully-grouted sections can be identified and differentiated from partially-filled and empty sections. The filling condition of thick-walled (rigid) ducts cannot be determined from the impact-echo line scans.

## ACKNOWLEDGMENTS

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## REFERENCES

- Carino, N. J., Sansalone, M. and Hsu N. N., 1986, A Point Source-Point Receiver, Pulse-Echo Technique for Flaw Detection in Concrete: *ACI Materials Journal*, **83**, 199-208.
- Gibson, A. and Popovics, J. S., 2005, Lamb Wave Basis for Impact-Echo Method Analysis: *ASCE Journal of Engineering Mechanics*, **131**, 438-443.
- Ryden, N., Lowe, M., Cawley, P. and Park, C., 2006, Non-contact surface wave measurements using a microphone: *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP 2006)*, Seattle, April 2-6, 2006.
- Sansalone, M.J. and Streett, W.B., 1997, *Impact-echo – Nondestructive Evaluation for Concrete and Masonry*, Bullbire Press, Ithaca, NY.
- Zhu, J., 2005, *Non-contact NDT of concrete structures using air-coupled sensors*, Ph.D. dissertation, the University of Illinois at Urbana.
- Zhu, J. and Popovics, J. S., 2001, Non-contact detection of surface waves in concrete using an air-coupled sensor: *Review of Progress in Quantitative Nondestructive Evaluation*, **20B**, edited by D.O. Thompson and D.E. Chimenti, 1261-1268. American Institute of Physics, Melville, NY.
- Zhu, J. and Popovics, J. S., 2005, Non-contact imaging for surface-opening cracks in concrete with air-coupled sensors: *Materials and Structures*, **38**, 801-806.