

Developments in air-coupled contactless sensing for concrete

John S. POPOVICS¹, A. GIBSON², K. HALL¹, S. W. SHIN³

¹ *Department of Civil and Environmental Engineering University of Illinois, Champaign-Urbana, USA, johnpop@illinois.edu*

² *Chased Technologies, Perth, AUSTRALIA*

³ *Division of Safety Engineering, Pukyong National University, Busan, KOREA*

Abstract

Recent developments in contactless, air-coupled sensing of seismic and ultrasonic waves in concrete are presented. Contactless sensing allows for rapid, efficient and consistent data collection over a large volume of material. Two inspection applications are discussed: air-coupled bridge deck scanning using seismically generated waves, and internal material reconstruction using ultrasonic tomography. The first application aims to locate and characterize shallow delamination defects within concrete bridge decks. Impact-echo is applied to defected concrete slabs using air coupled sensors. Next, efforts to apply air-coupled ultrasonic tomography to concrete are discussed. Various solutions for tomographic inversion and improvement of SNR are evaluated. Preliminary results are presented for air-coupled ultrasonic tomography to solid elements to locate internal defects. The results demonstrate that, with continued development, air-coupled ultrasonic tomography can provide improved evaluation of unseen material defects within structures.

Résumé

Des développements récents des mesures sans contact, par couplage par air pour les ondes sismiques et ultrasonores dans le béton, sont présentés. Les transducteurs sans contact permettent une collecte de données rapide, efficace et cohérente sur un grand volume de matériau. Deux applications sont discutées : l'inspection sans contact d'un tablier de pont par génération d'ondes sismiques et la reconstruction de la structure interne d'un matériau par tomographie ultrasonore. La première application vise à localiser et à caractériser les défauts de délamination peu profonds dans les tabliers de pont en béton. La technique impact-écho est appliquée ici sur des dalles de béton présentant des défauts en utilisant des transducteurs à couplage par l'air. Ensuite, les travaux engagés pour réaliser une image tomographique ultrasonore sans contact du béton sont présentés. Les diverses solutions pour l'inversion tomographique et l'amélioration du rapport signal/bruit sont évaluées. Des résultats préliminaires sont présentés pour la tomographie ultrasonore à couplage par l'air d'éléments solides, afin de localiser des défauts internes. Les résultats démontrent que la tomographie ultrasonore sans contact peut améliorer l'évaluation de défauts cachés du matériau dans les structures.

Keywords

Concrete, Imaging, Impact Echo, Ultrasound, New sensors

1 Introduction

Of the nearly early 600,000 bridges in the United States, 27% were rated as structurally deficient or functionally obsolete in 2003 [1]. Intelligent renewal of service life is enabled if rapid, accurate and reliable non-destructive scanning technologies (such as that proposed here) are applied to assess transportation infrastructure components (e.g. bridge decks) with

minimal disruption to structure service. When applied properly, timely and accurate NDE and assessment yield significant benefit for practice though longer-lasting, more cost-effective systems that can better serve the users and reduce congestion and transportation costs while at the same time recouping the yearly high costs associated with bridge structure maintenance. Two specific bridge deterioration problems are studied here: corrosion-induced deck delamination and cracking and voiding within concrete bridge columns.

2 Bridge deck scanning

The investigators have established the basic requirements for non-contact sensors for contactless air-coupled impact-echo and seismic-based tests. A point impact source will be used. A suitable impact source for detecting delaminations with acoustic sensors should have relatively high force amplitude, relatively low frequency content, and minimal production of ancillary acoustic noise. All of features are provides by a small hand-held hammer but only when the vibration of the handle is muted; the muting is achieved by wrapping the handle with insulating foam.

Several commercially-available air-coupled sensors have been investigated for the purpose of detecting seismic signals in concrete. All of the sensor types are able to detect impact-echo and seismic responses from concrete in a fully contactless manner. Of these, the conventional vocal microphone provides the lowest sensitivity and frequency bandwidth. However, this sensor is still able to collect impact echo and seismic data without any external bias or noise shielding, and allows close placement of the sensor to the surface. Thus the Shure SM-58 vocal microphone was selected for implementation in the tests.

Air-coupled impact-echo tests were carried out on a manufactured concrete test slab. This slab simulates a typical bridge deck in the state of Illinois, with a total thickness of 200mm and steel cover depth of approximately 50 mm. The slab contains pre-placed defects. Corrosion-induced delamination defects are simulated by placing a double layer of thin polymer sheets on top of the steel bar mesh. Air coupled impact echo data were collected at 25 mm spacing in a grid around the area above a 400mm x 600mm top delamination defect. The frequency domain data are represented in line scan and area scan images. Line scan images of frequency data collected across the center of the delamination length are shown in Figure 1. The boundaries of the defect are indicated with dashed lines. Clear indications of high amplitude in the frequency spectra are seen at specific frequencies when the tests are located above the defect. The three frequencies that are observed match that of the fundamental and first harmonics of the flexural vibration of the defect, which were predicted by FEM computations. Thus we conclude that the proposed air-coupled impact echo testing configuration is sensitive enough to capture meaningful data from defects, since the extent of delaminated area is indicated by high amplitude at these various frequencies. This sort of data presentation offers an effective manner to indicate the location and extent of delamination in an image.

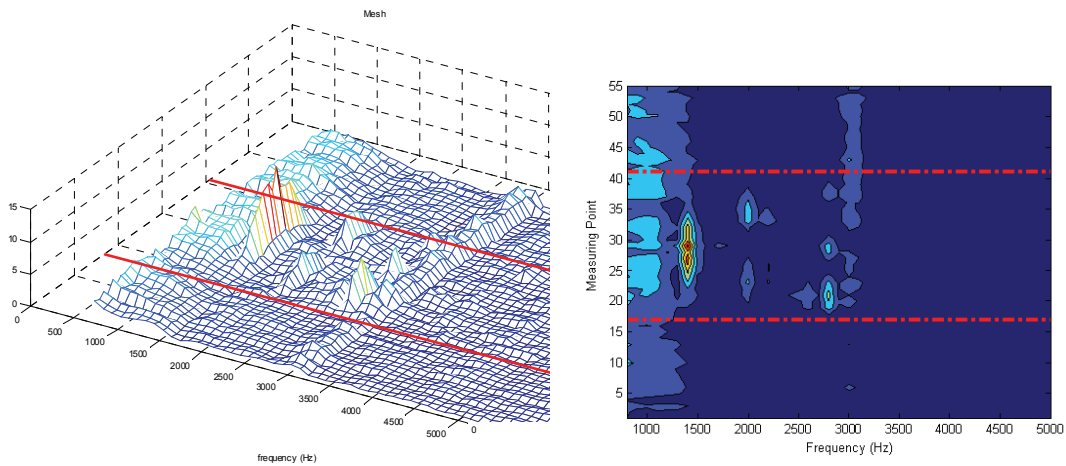


Figure 1. Impact-echo line scan images collected across center of 400mmx600mm delamination: (left) 3-D mesh plot of frequency vs. scan spacing; (right) frequency contour plot. Defect boundaries indicated with dashed line.

3 Ultrasonic Tomography

Tomography is a process of reconstructing a cross-sectional image using ray projection measurements through the section. Resolution of these images is generally limited by the ray coverage density and the wavelength of the energy used in measurements [2]. In classical solutions the reconstruction can be performed by a two-dimensional convolution or a matrix inversion, however these solutions require specific source-receiver geometries and assume straight ray paths. These geometry restrictions can rarely be met when imaging solid objects, and the high contrast in material acoustic velocities lead to nonlinear ray paths. Iterative methods are often used for tomography of solids to accommodate different geometries and accurately model curved ray paths [2]. The program 3DTOM developed by the Jackson and Tweeton [3] models nonlinear ray paths in iterative solver and is often used for concrete tomography [4,5]. The large difference in acoustic impedance between concrete and air brings a large reduction of transmitted energy at the interface of air and concrete. High attenuation of ultrasonic waves traveling through concrete adds to this problem. Special transducers and signal processing methods have been applied to overcome these challenges [6].

3.1 Test Specimens

After a developing an air-coupled measurement system and tomographic reconstruction algorithm, a set of specimens were fabricated to test the system. Polyvinyl Chloride (PVC) was selected for the first specimens because its attenuation is somewhat lower than that of concrete and is absorptive rather than scattering. This leads to clearer transmitted signals for the initial trials. Three cylindrical phantoms 150 mm in diameter were prepared with various inclusions, as shown in Figure 2.

A second set of specimens has been cast of concrete. These cylinders will be used to further test the developed imaging method. The concrete specimens were cast with geometries and inclusions nearly identical to the PVC specimens.



Figure 2. PVC phantoms

3.2 Testing procedure

For this work an air-coupled ultrasonic testing system was developed using time averaging and pulse compression of a frequency modulated signal. Two Senscomp 600 capacitive micro-machined ultrasonic transducers (CMUTs) were used to send and receive the signals. CMUTs provide a better transmission into air than conventional piezoelectric transducers. These sensors each had a central frequency of 55 kHz. The applied chirp ranged from 75-40 kHz and had a time-bandwidth product of 40. This theoretically provides a SNR improvement of 16 dB in pulse compression. Each signal was collected over 4000 time averages and then cross-correlated with a reference signal through air only. As seen in Figure 3, a sharp peak in the resulting signal corresponds to the arrival time of the pulse. By subtracting the time of flight in the reference signal, the arrival time through solid and air is calculated.

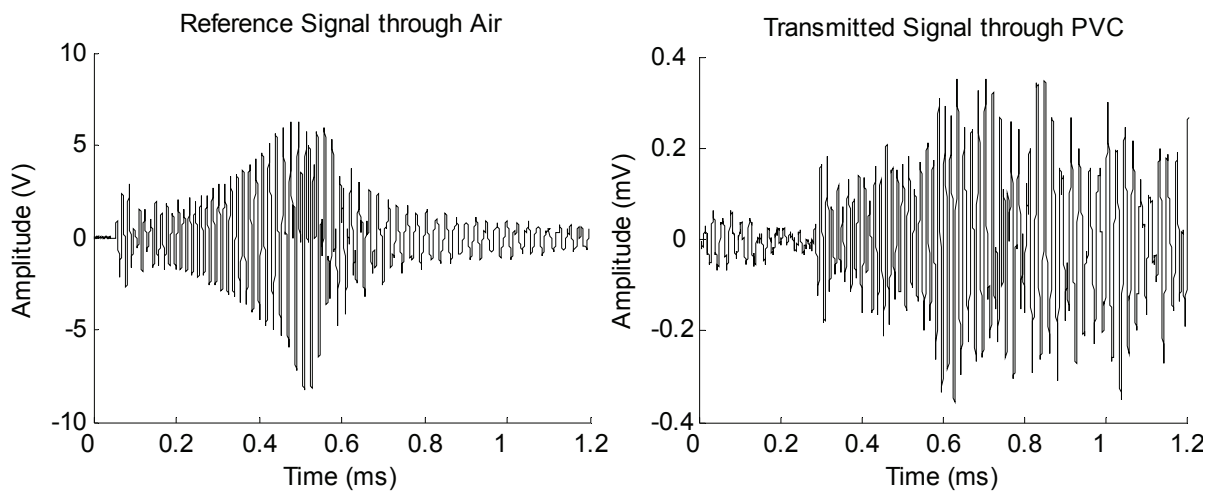


Figure 3. Collected time domain signals: reference signal through air (left) and transmitted signal through PVC (right)

Measurements were made through each specimen by direct transmission (180° transducer spacing) and at a 40° offset with an air gap of 30 mm. The specimen was rotated in 10° increments to collect a total of 54 projection measurements. Because of the high velocity contrast between the air and solid, it can be assumed that the path of the first arriving wave is direct from the transducer to the nearest point on the cylinder. The time of flight through the air gap was subtracted from the total time so that the sources and receivers could be represented on the surface of the cylinder in the reconstruction model. The third author has

developed an algorithm, which is similar to that in the 3DTOM program [3] but with a more convenient format for the work in this paper. A field of 24x24 pixels was used for the model. The known velocity of PVC was used as the initial guess for the velocity field. The final images were interpolated bi-linearly for display and interpretation.

The results of the tomographic reconstructions are shown in Figure 4. In each of the images the actual shape and location of the inclusion is indicated by a white line. Generally the reconstructions capture the shape and location of each of the inclusions. Some additional high and low velocity regions appear as artifacts of the reconstruction. These artifacts could be reduced, and the contrast and resolution improved if a greater number of ray measurements were made. The steel bar appears as a low velocity inclusion because of a problem in the signal processing. The wave that bypasses the bar is greater in amplitude than the wave transmitted through the bar; because the difference in their arrival times is less than $\frac{1}{2}$ of the wavelength, the signal through the steel is eliminated by the signal processing as unwanted noise. The use of a higher frequency might eliminate this problem, but would limit the depth of penetration possible through concrete.

Preliminary tests have also been performed on one of the concrete specimens. Measurements were made through the void concrete specimen by direct transmission (180° transducer spacing). The specimen was rotated through 90° in 10° increments so that a range of measurements could be seen for comparison through the void and avoiding it. The measurements of transmission through concrete cylinders have been less successful. There is no clear trend in the variation of the travel times through concrete. Although no attenuation tomographs have been computed so far, it was decided to also compare the amplitudes of the transmitted signals. There is a strong trend in the amplitude of the transmission through the PVC specimen with lower amplitudes when the wave passes near the void. The amplitudes of the signals transmitted through concrete show a similar trend, although the magnitude of the differences is lower and the variation is much higher.

4 Conclusions

Viable air-coupled impact-echo tests are possible with impactors and conventional microphones. Multiple flexural vibration modes of the delamination can be used to characterize and image defects in an effective manner. Fully air-coupled ultrasonic measurements were successfully obtained through three 150 mm PVC specimens. The reconstructed tomographs indicate the shape and location of inclusions. Further development is necessary to detect high velocity inclusions and demonstrate possible resolution improvements. Measurements through concrete were less successful, although some indication of the void is given by the attenuation measurements.

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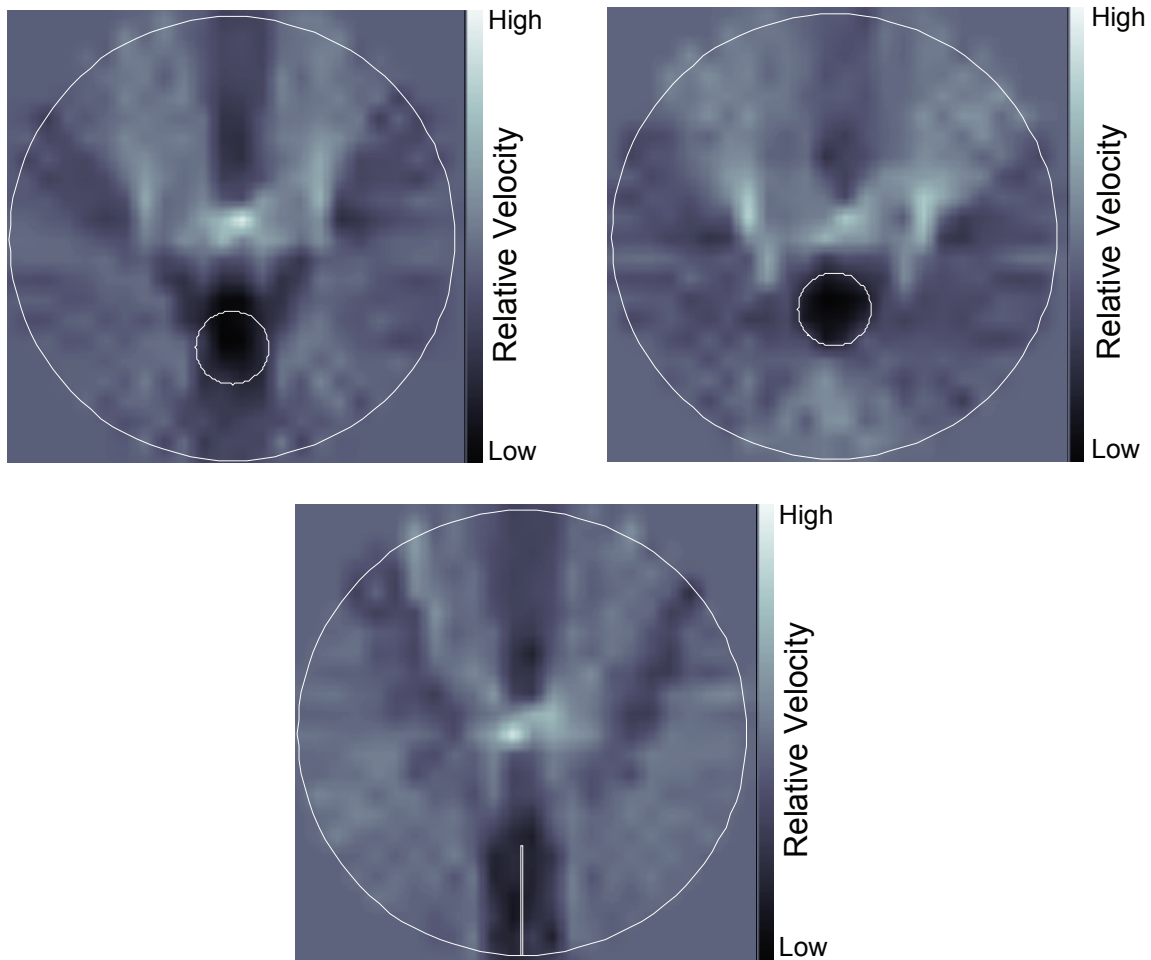


Figure 4. Tomographic images of the three PVC specimens. Upper left is the void. Upper right is the steel bar. Lower is the crack.

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