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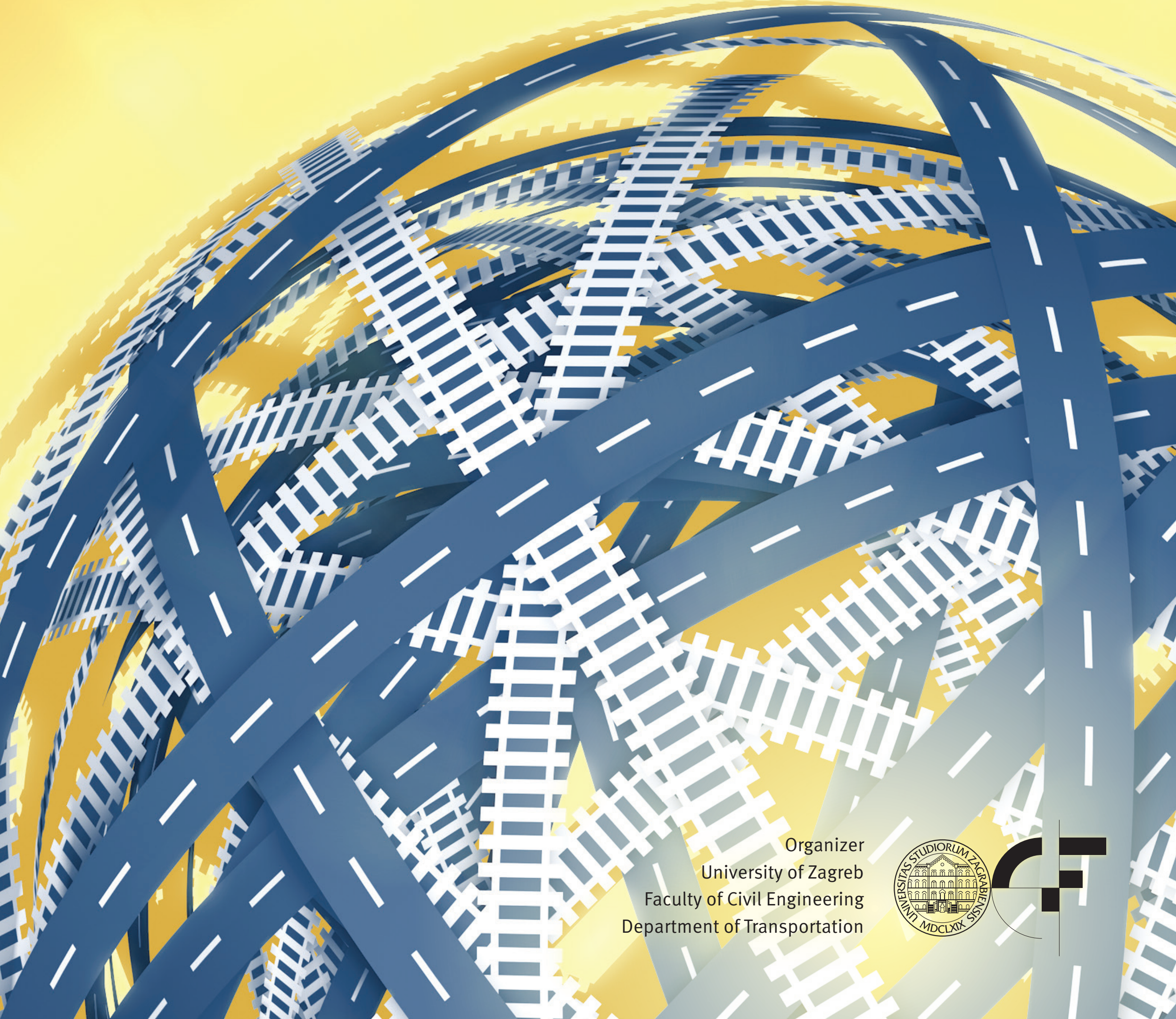
23–25 May 2016, Šibenik, Croatia

# Road and Rail Infrastructure IV

Stjepan Lakušić – EDITOR



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# Road and Rail Infrastructure IV

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# USE OF AIR-COUPLED SENSING IN THE ASSESSMENT OF BRIDGE DECK DELAMINATION AND CRACKING

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## Abstract

Air-coupled acoustic sensing opens opportunities to dramatically increase the speed of data collection. The evaluation of feasibility of air-coupled sensing led to the development and implementation of a prototype air-coupled ultrasonic system (ACUS) for simultaneous collection of impact-echo and surface wave data in concrete bridge decks. The basic sensor unit of ACUS is a hexagonal air-coupled sensor array, which includes a solenoid-driven impact source at the center and six air-coupled sensors (ACSs) with parabolic acoustic reflectors (PARs) at vertices of the hexagon. Primary interests of air-coupled acoustic testing are related to detection of delamination using impact echo (IE), and measurement of concrete modulus and evaluation of depth of vertical cracks using surface wave testing. The performance of the hexagonal arary was evaluated on a validation bridge containing numerous artifical defects (delaminations, surface-breaking cracks, segregated aggregates, partially grouted tendon ducts, and accelerated corrosion test regions). The results from performance evaluation on delaminated and cracked sections of the validation bridge are presented.

*Keywords: bridge decks, delamination, cracks, impact echo, surface waves, air-coupled sensors, microphones*

## 1 Introduction

Two problems of high concern in deterioration of concrete decks are development of delamination and vertical, surface breaking cracks. Delamination is most commonly caused by rebar corrosion, but it can be also induced as a result of repeated overloading, freeze and thaw action and other sources. Similarly, vertical cracks can be a result of corrosion, concrete shrinkage and other causes. Delamination and vertical cracks are illustrated in Figure 1. As shown in the figure, vertical cracks can propagate to any depth, while delaminations are generally horizontal cracks of a varying depth.
Delamination has been most effectively evaluated using impact echo (IE) method [1, 2]. However, in actual surveys of reinforced concrete components, especially bridge decks using contact sensors, a lower test production rate and somewhat inconsistent coupling conditions are encountered. Both issues can be effectively improved by using contactless or air-coupled sensors (microphones). Previous studies have demonstrated that air-coupled sensors are effective in improving signal consistency and test speed in IE testing [3, 4, 5].
The following sections discuss the use of air-coupled sensing in evaluation of delamination and characterization of vertical cracks with respect to their depth. The first part of the paper discuss the basics of air-coupled sensing and use of parabolic reflectors to enhance the signal. The second part illustrates air-coupled sensing by presenting results from delamination and vertical crack surveys.

**Figure 1** Vertical crack on the surface of a bridge deck (left), a core with a vertical crack (middle), and a core with a vertical crack and delamination (right)

## 2 Air-coupled sensing and parabolic acoustic reflectors

AIr-coupled acoustic sensors (measurement microphones) have many advantages. However, because of a low microphone sensitivity, the signal analysis is often complicated due to low signal-to-noise ratios of the sought signal. Several issues need to be overcome. One of them is a commonly weak signal as a result of a large impedance difference between the air and concrete, resulting in significant energy losses between the source and receiver. The other common problem is often present traffic noise in actual field testing, mostly at frequencies less than a few kHz. To improve the sensitivity of an air-coupled sensor (microphone), is by using a parabolic acoustic reflector (PAR) [5, 6].
A typical wave field during air-coupled testing with PAR is illustrated in Figure 2. The image represents a snapshot of a finite element simulation using finite element program ABAQUS. The generated wave fields are a result of application of an impact on the surface of a concrete plate. The movement of the plate surface as a result of propagation of impact induced stress waves will lead to generation, or "leaking", of acoustic wave energy into the interfacing air. One of the dominant components of the response to an impact will be first symmetrical Lamb mode ($S_1$ZGV), which in this case will correspond to the frequency of oscillations for the full plate thickness. The resulting periodical waves can be oberved in the figure. The second dominant waves are leaky surface waves, which represent leakage of the surface waves in the plate into air. According to the Snell's law, and based on the typical surface wave velocity in concrete, and compression wave velocity in the air, the leaky angle is about eight degrees. The third marked component represents the direct acoustic wave as a result of the impact. Finally, some higher air-pressure waves can be observed within the PAR.
Parabolic acoustic reflectors (PARs) were introduced to improve the signal-to-noise ratio of the signal. The PARs operate under the assumption that any incident plane wave parallel to the axis of the parabolic surface is reflected toward the focal point. Because the length of the wave paths to the focal point are the same, the acoustic waves of the same frequency will be in phase at the focal point. Therefore, the use of parabolic reflectors can effectively enhance the valuable stress-wave components in the air-coupled IE testing. An extensive numerical and experimental study was conducted to evaluate the effect of the size, shape and position of the PAR on the air-coupled IE testing [7]. As shown in Figure 3, for evaluation of concrete slabs of about 200 mm thicknes, an optimum PAR diameter is about 150 mm, and the rim angle should be about ninety degrees. The PAR should be within a distance equal or slightly larger than the plate thickness. Within that distance, the signal of the first symmetrical Lamb mode will be fully in phase.

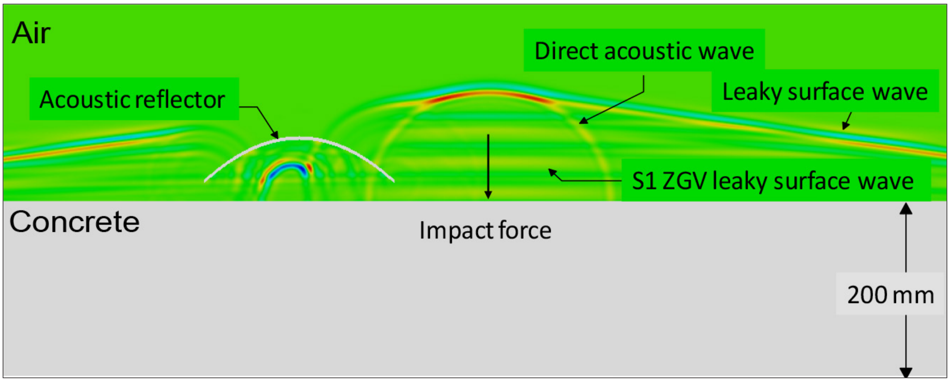


**Figure 2** Snapshot of the air-pressure field generated by an impact on the surface of a concrete plate

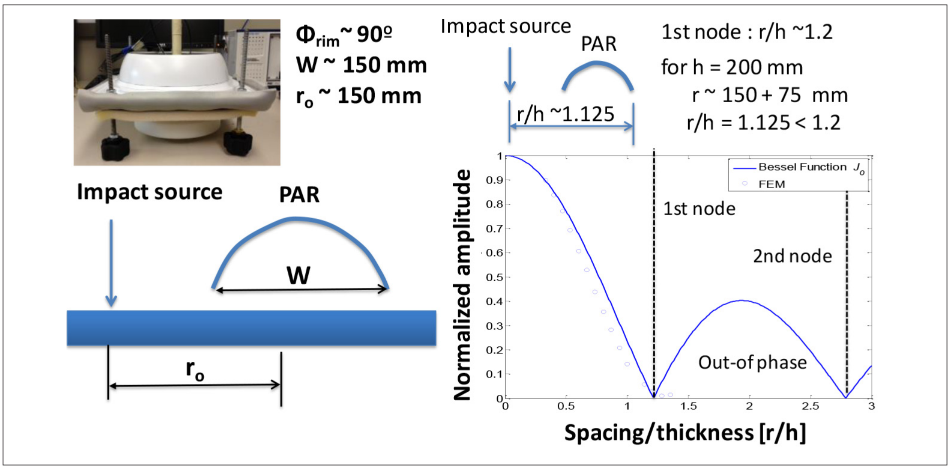


**Figure 3** Optimal parameters for the PAR

**Figure 4** Hexagonal air-coupled acoustic array: parabolic reflectors with microphones and an impact source in the center (left), and application of the array in evaluation of a concrete dam

Six PARs with acoustic sensors (microphones) in there focal points were assembled into a hexagonal acoustic array configuration, as shown in Figure 4. The hexagonal arrangement was selected to enable building of larger arrays from the same units. However, the unit itself can be used as an independent system for delamination detection using impact echo principles, and for depth estimation of surface breaking cracks using surface wave testing principles. Both applications are illustrated later. The unit consists of six PARs of a 150 mm diameter and a linear solenoid type impact source in the center of the array. In the case of surface wave testing, a source outside the perimeter of the hexagonal array needs to be used. The radial distance between the source and microphones is 150 mm. The height of the PARs can be varied. However, the system is typically used with the distance between the surface of the tested element and microphone from 60 to 80 mm.

## 3 Delamination and crack assessment by hexagonal array

The implementation of the hexagonal acoustic array is illustrated by the results of delamination and vertical crack evaluation on the Rutgers Validation Bridge (RVB). The RVB is a bridge structure 9 m long, 3.6 m wide, with a reinforced concrete deck 20 cm thick supported by three steel girders. The deck has numerous embedded artificial defects: delaminations, vertical cracks, ducts of various type and grouting conditions, concrete segregation, and an area undergoing accelerated corrosion. Types of defects embedded in the deck are shown in Figure 5.

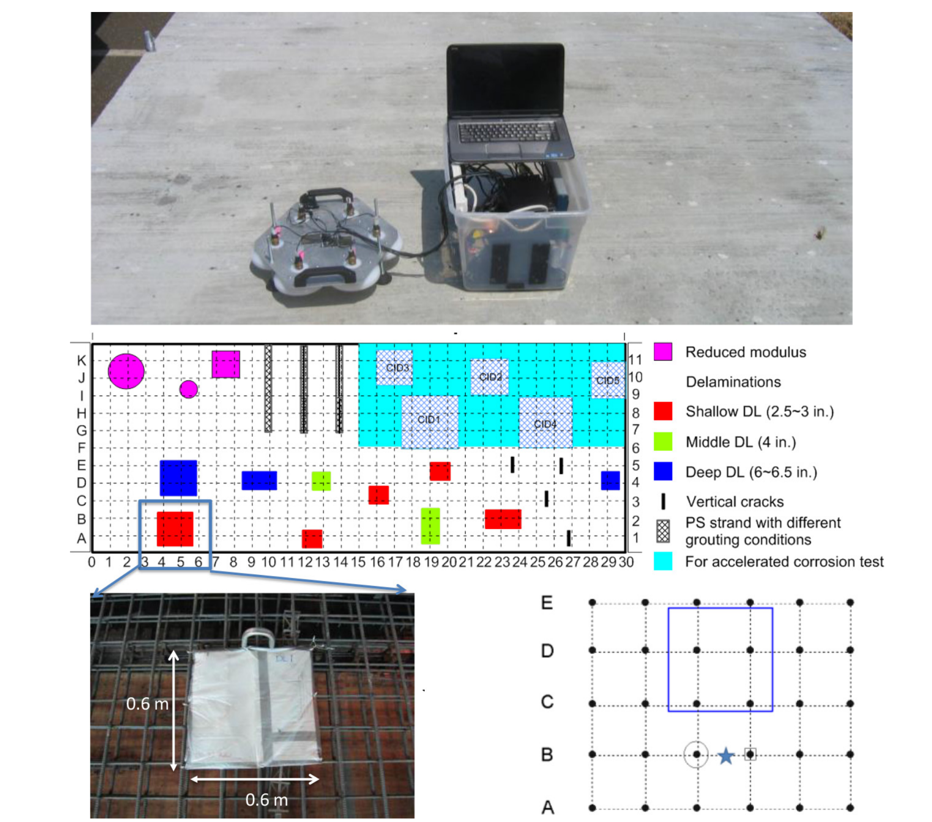


Figure 5 Hexagonal air-coupled acoustic array on the validation bridge (top), schematic of embedded defects and deterioration in the bridge (middle), and the delamination evaluated (bottom)

The array was used in evaluation of a delamination of 0.6 m by 0.6 m, and about 7 cm deep. The survey was conducted by moving the center of the hexagonal array in 0.3 m increments in both longitudinal and transverse directions. As illustrated in Figure 6, the dominant frequencies in the spectra of the response of the deck to an impact, clearly point to frequencies describing a sound and delaminated deck. The sound deck condition is established when the dominant peak matches the frequency of the first symmetrical Lamb mode. The delaminated condition is recognized through a much lower dominant frequency of flexural vibrations of the upper delaminated section of the deck.

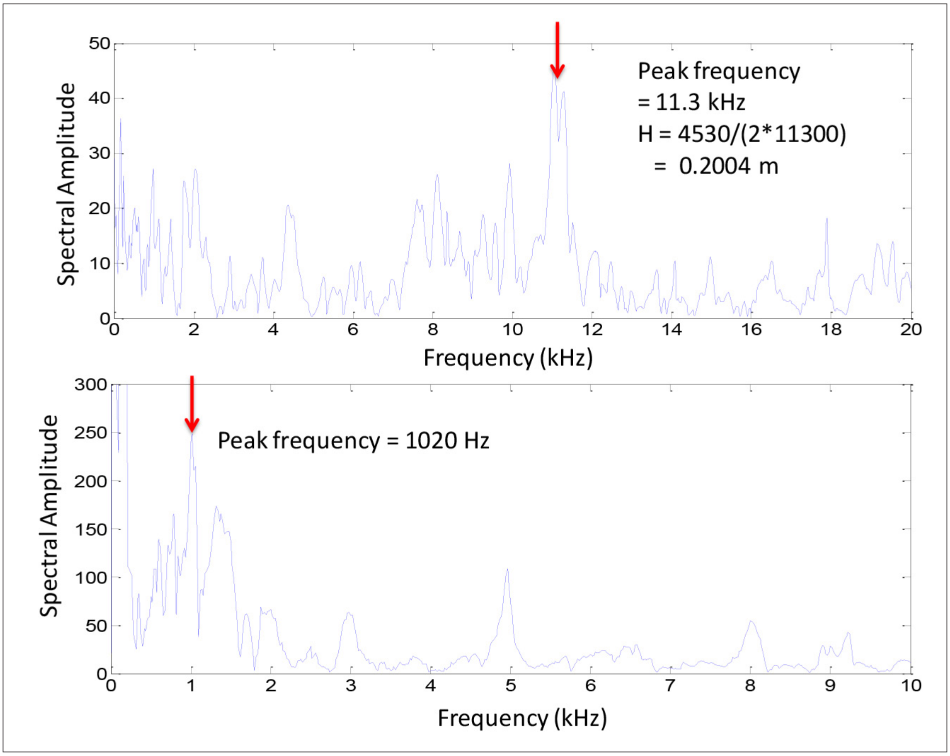


**Figure 6** Frequency spectrum from IE survey at a location with no delamination (top), and a location with shallow delamination (bottom)

A more accurate position and description of a delamination can be achieved by using information from two receivers symmetrically placed with respect to the source [8]. This is illustrated in Figure 7 by a frequency response plot. The receivers in this case were moved in 0.15 m increments. Presentation using information from two receivers clearly points to the position of the center of the delamination, and at the same time describes zones of the delamination away from the center where the dominant response is, as expected, going to be at frequencies corresponding to higher flexural modes.

Finally, the air-coupled acoustic array was used in estimation of the depth of four vertical surface breaking cracks in the deck. The evaluation was conducted by placing two of the array's sensors symmetrically with respect to the crack, and application of an impact in line with the sensors, as shown in Figure 8. The depth of the cracks was estimated using the procedure outlined in [3]. The results provide a generally good agreement between the estimated and actual depth of the cracks, with the actual depth being slightly underestimated.

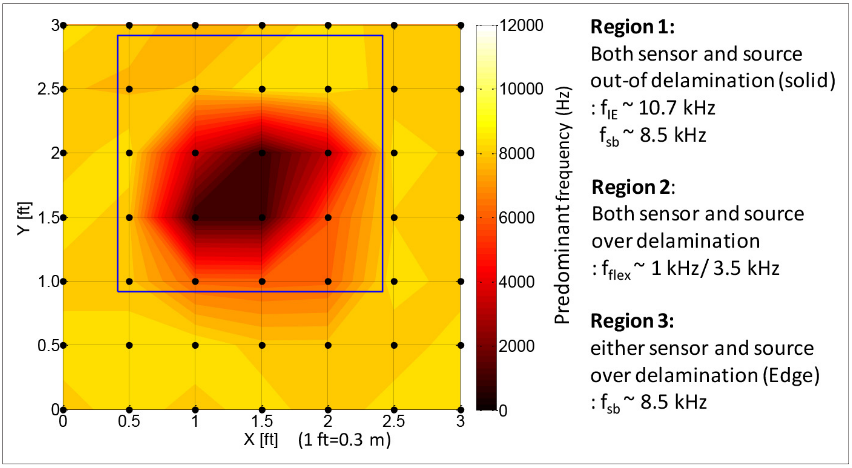


**Figure 7** The frequency response surface above and in proximity of a 0.6 by 0.6 m delamination

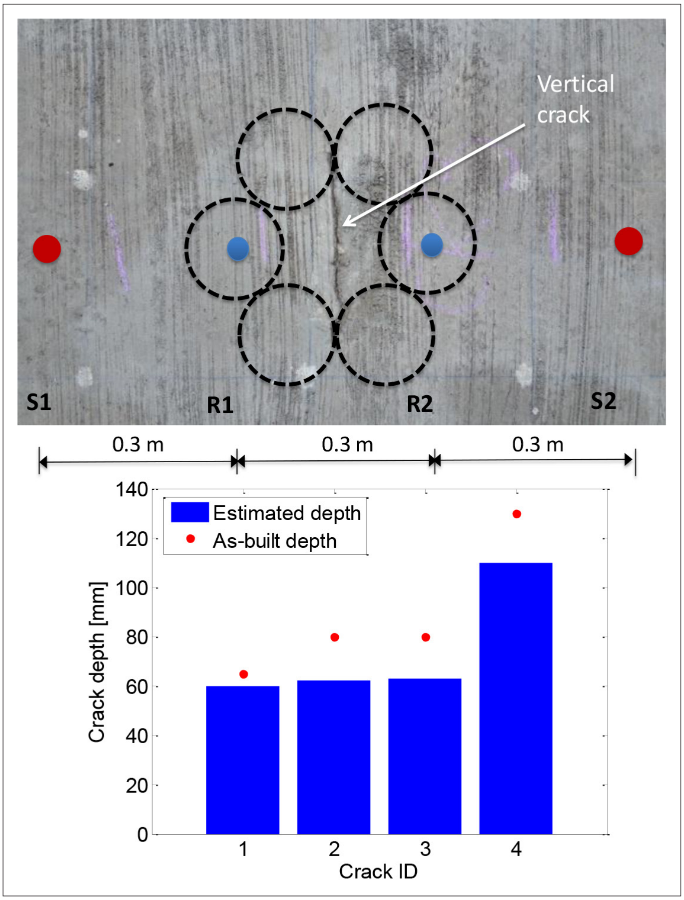


**Figure 8** Placement of the acoustic array with respect to the vertical crack (top), and the comparison of estimated and actual depth of cracks (bottom).

## 4 Conclusions

Air-coupled sensing can be effectively used, instead of contact sensing, in the assessment of delamination and vertical cracks. Placement of receivers in an hexagonal arrangement around the source significantly improves the speed of data collection. It also enables a more advanced impact echo analysis from signals of two symmetrically placed receivers with respect to the source, and evaluation of depth of vertical cracks using an external impact source.

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