Development of an Efficient Air-Coupled Impact-Echo Scanner for Concrete Pavements

Robin GROSCHUP [1], Christian U. GROSSE [1]
[1] Technical University of Munich, Chair of Non-destructive Testing, Munich, Germany
Contact e-mail: robin.groschup@tum.de, zfp@cbm.bgu.tum.de, grosse@tum.de

Abstract. Aging roadways can be affected by internal defects not visible from the surface. This is especially the case for highways build in concrete where horizontal cracks or delaminations can adversely affect remaining lifetime. Therefore a non-destructive testing system to demarcate highly endangered portions of a roadway is very desirable. Constructive refurbishment could be better prioritized and overall safety would be optimized with reduced cost.

A major challenge for such a system is the need for a high acquisition speed since long stretches of the road network have to be examined. Air-coupled impact-echo techniques have a high potential to indicate delamination defects with an efficient measurement setup. We implemented an automated scanning device based on the impact-echo method for fast data acquisition in continuous motion. Low signal to noise ratio of the acquired air coupled signals is a very relevant problem and is overcome by a combination of an optimized sensing concept with a multiple excitation strategy. We demonstrate the efficiency of our prototype scanning device with results on test structures with known flaws and on real concrete pavements. Routine operations on highways are envisaged.

1. Introduction

1.1 Background

Despite significant developments regarding non-destructive testing (NDT) devices for the evaluation of concrete structures, application of most techniques can in practice be hampered by operational constrictions. This holds particularly true when there is a need to gain information about extensive areas. An example where large areas of an engineering structure have to be examined with respect to certain types of damage is the case of concrete pavements. Typical defects like delaminations, horizontal cracks or debonding phenomena are not visible from the surface but shorten the remaining lifetime and even pose a risk to operational safety.

To image internal defects in concrete pavements in an efficient and practical way no out-of-the-box NDT systems exist. Ultrasonic instruments such as dry-coupled shear wave arrays can produce high resolution images of the internal state of concrete elements. But due to the restriction of the necessary physical coupling between sensor and tested object operational effort and overall testing time can be too expensive for the specific measurement task. On the other hand the contactless radar technique can be applied with high scanning speeds, but the resulting resolution is not capable to image small scale cracks and limits the range of application to the detection of relatively coarse features like mounting parts (e.g. tendon ducts, rebar) or voids. To overcome the disadvantages of the mentioned technologies air-coupled mechanical wave based methods can offer useful alternative approaches. The main advantage of air-coupled sensing lies in the possibility to implement a scanning device that can be moved over a surface in continuous motion. Whereas air-coupled high frequency ultrasonic methods show promising results in small scale applications and laboratory settings, they are still difficult to handle in field conditions. Therefore, a new approach to the air-coupled impact-echo (IE) method is presented in this study.

1.2 Air-Coupled Impact-Echo

Methods applying mechanical impactors to study the propagation of stress waves have been shown to have great potential to be implemented in air-coupled fashion [1, 2, 3, 4]. Among these methods is the dispersion analysis of surface waves (e.g. spectral analysis of surface waves [5]) and the IE technique [6, 7]. During an IE test stress waves are induced by a mechanical impact (e.g. impact hammer or steel ball drop) on the surface of the tested concrete specimen. The excited stress waves are normally measured at a single sensor location in the vicinity of the impact point. In the usual IE processing scheme the sensor recordings are transformed from time domain to frequency domain. In plate like structures the resulting spectra show a dominant frequency that can be related to the plate thickness. Historically this relation was first established empirically and later explained by Lamb-Wave theory [8].

The IE method has several operational advantages: At first the method provides a very high precision for thickness measurements of plate like structures (accuracy depends on proper calibration) and it can be implemented with relatively few and simple components. Usually only one sensor and one impactor are necessary to perform an IE measurement. Furthermore, the response of an IE measurement is very sensitive to certain types of damage like delaminations [9]. This is due to the fact that the broadband nature of the impact excitation can provoke flexural vibrations of delaminated regions. Since such flexural vibrations have a strong out of plane component of particle velocity sound waves are radiated from damaged regions with significantly different amplitudes and frequencies than from undamaged regions. Since sensing and signal generation happen in close proximity the method also provides an immediate lateral localization of the detected damage.

Although IE was successfully implemented in a scanning manner with contact type transducers [10] air-coupled sensing represents a promising approach to reduce mechanical complexity and thereby enhancing scanning speed and simplifying routine applications. However, due to the superposition of ambient noise, impact noise and radiating elastic waves the implementation of an air-coupled IE device is not a straightforward task. A further requirement is the need for high spatial data coverage since the information gained from a single IE measurement is localized in a region around the impact location.

The main objective of the presented work is the development of a NDT device based on the IE method to detect damage in concrete pavements in a scanning manner addressing the aforementioned challenges. At first an appropriate sensor is introduced to overcome the above mentioned noise problems in air-coupled IE setups. Furthermore, the implementation of an impact source and the combination of these components in an automated scanning system is described. Finally, first results acquired with a prototype device on a field scale test slab with artificial flaws and exemplary measurements on real concrete pavement sections are presented.

2. Design of a Scanner Prototype

2.1 Microphone Array Sensor

The sensing element for air-coupled IE measurements would ideally have a selective sensitivity for sound waves radiated from the specimen under test. All other acoustic sources, like ambient noise and impact noise should be suppressed to facilitate signal processing and not to distort final data interpretation. This requirement can be met by tuning the directional sensitivity of an array of microphones. Based on numerical simulations of wave propagation and radiation an array arrangement of MEMS microphones was designed and optimized to the requirements to test typical engineering plate-like concrete structures such as walls and pavements in a thickness range from 15-30 cm [11]. The array consists of 35 single microphones carried on a printed circuit board (Fig. 1 (a)). Signals of individual microphones are summed by analog circuitry.

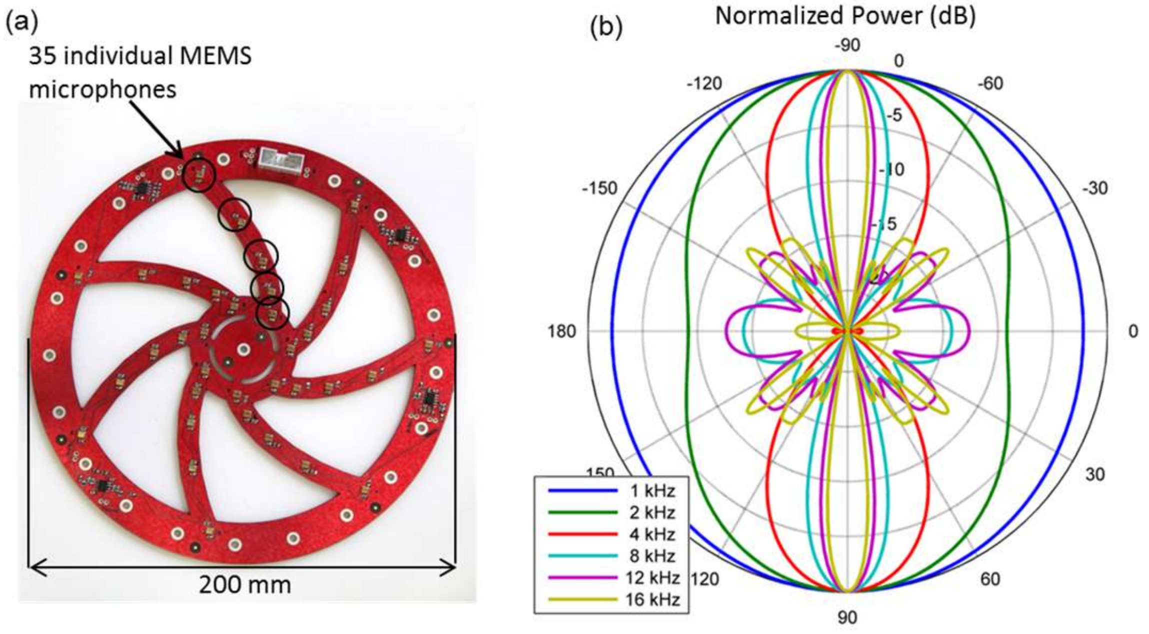

Fig. 1. Microphone array for IE measurements: (a) Printed Circuit Board carrying 35 individual MEMS microphones. (b) Directivity pattern of microphone array in the plane perpendicular to the array extension.

Due to the chosen spatial arrangement the sensor board shows a frequency dependent directivity pattern (Fig. 1(b)) with a maximum sensitivity for sound waves incident perpendicular to the microphone arrangement. Sound waves hitting the array from the sides are recorded with lower sensitivity. This advantageous directivity is most prominent for frequencies greater than 2 kHz. In practice the relevant frequencies for data interpretation in an IE test setup will have a bandwidth roughly extending from 2 to 15 kHz. As a result of the directivity pattern of the microphone array desired signals like plane wave fronts arising from the impact generated thickness resonance mode will be recorded with a higher sensitivity than disturbing sounds that come from lateral directions.

2.2 Acoustic Scanner Assembly

After initial tests of the microphone array board under laboratory conditions [11, 12] a rolling trolley (Fig. 2) was constructed to perform line scan measurements in a semi-automated way. I.e. the trolley had to be moved manually whereas data acquisition and impacting was controlled in an automated way utilizing a rotary encoder. The trolley was built with a stiff aluminium frame to avoid structural resonances during rolling. The microphone array was put into an own enclosure with flexible suspension for vibration isolation.

To acquire signals that allow accurate data interpretation the impact should be pure elastic. A free falling steel ball would fulfill this requirement best. By using a solenoid driven impactor a good compromise between impact quality and automated signal generation with sufficient energy and repeatability was achieved. A further advantage of the solenoid impactor was the possibility to produce single impacts with high repetition rates (~ 8 impacts per second at current state) using simple electronic circuitry to control the solenoids. The frequency content of the impact signal can be adjusted by varying the mass of the impactor. Here, a 12 mm diameter steel ball together with an additional mass was mounted on the plunger of a double-acting solenoid (made by Tremba GmbH). A piezo element mounted on the movable plunger acted as a trigger source. An improvement of impact quality compared to previous studies [12] was achieved by modifying the impactor suspension within the trolley by rubber pads and better tuning of the power cycling of the solenoids.

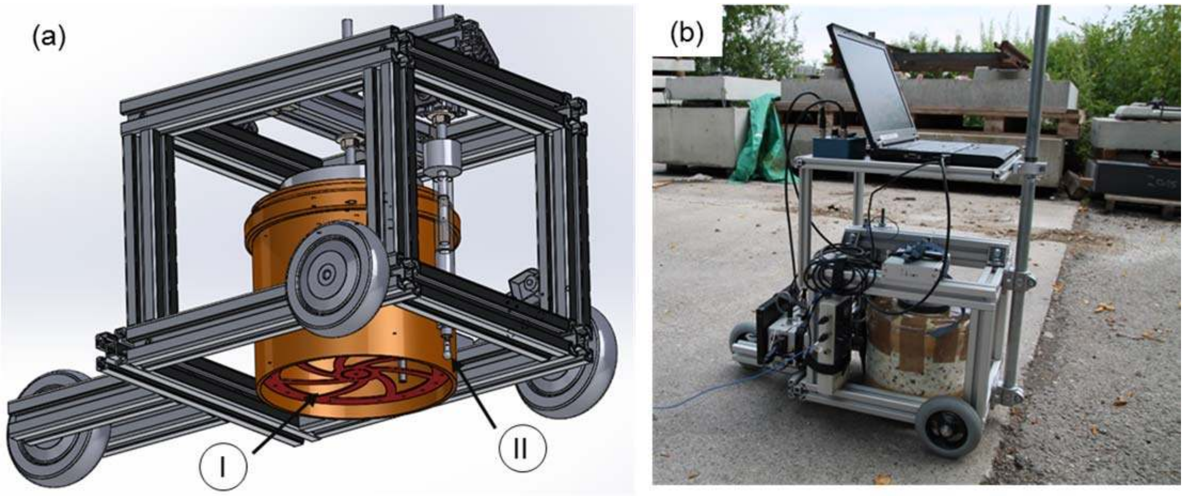

Fig. 2. (a) Design sketch of scanner trolley with microphone array (I) and solenoid impactor (II). (b) Implementation with measurement electronics and PC based user interface.

3. Measurements with the Scanner Prototype

3.1 Test Slab with Artificial Defects

The acoustic scanner prototype was first tested on a reinforced concrete slab with a nominal thickness of 30 cm (Fig. 3). Artificial flaws of different types were installed into the slab before casting (regions of varying thickness with foam inserts, delaminations as PTFE sheets in different depths and honeycombing by inserting loose gravel). Apart from these structures within the slab the backfill material was also varied simulating different foundation scenarios. One half of the slab was completely decoupled from the foundation by means of a rubber mat (Fig. 3 (b)). On the other half of the slab concrete was directly poured onto a foundation made from the same concrete as used for the slab. The foundation was built with cavities containing different materials (Fig. 3 (a)). To produce a two-dimensional IE scan, the prototype device was moved over the test slab along multiple scan lines with 10 cm separation. The impactor was configured to be activated every 2.5 cm. A total area of approximately 8 m^2 was tested in 15 minutes total testing time. Thus, a much faster testing was achieved compared to contact-based IE testing and contact-based ultrasonic testing. Testing time was comparable to a handheld single-antenna ground penetrating radar survey.

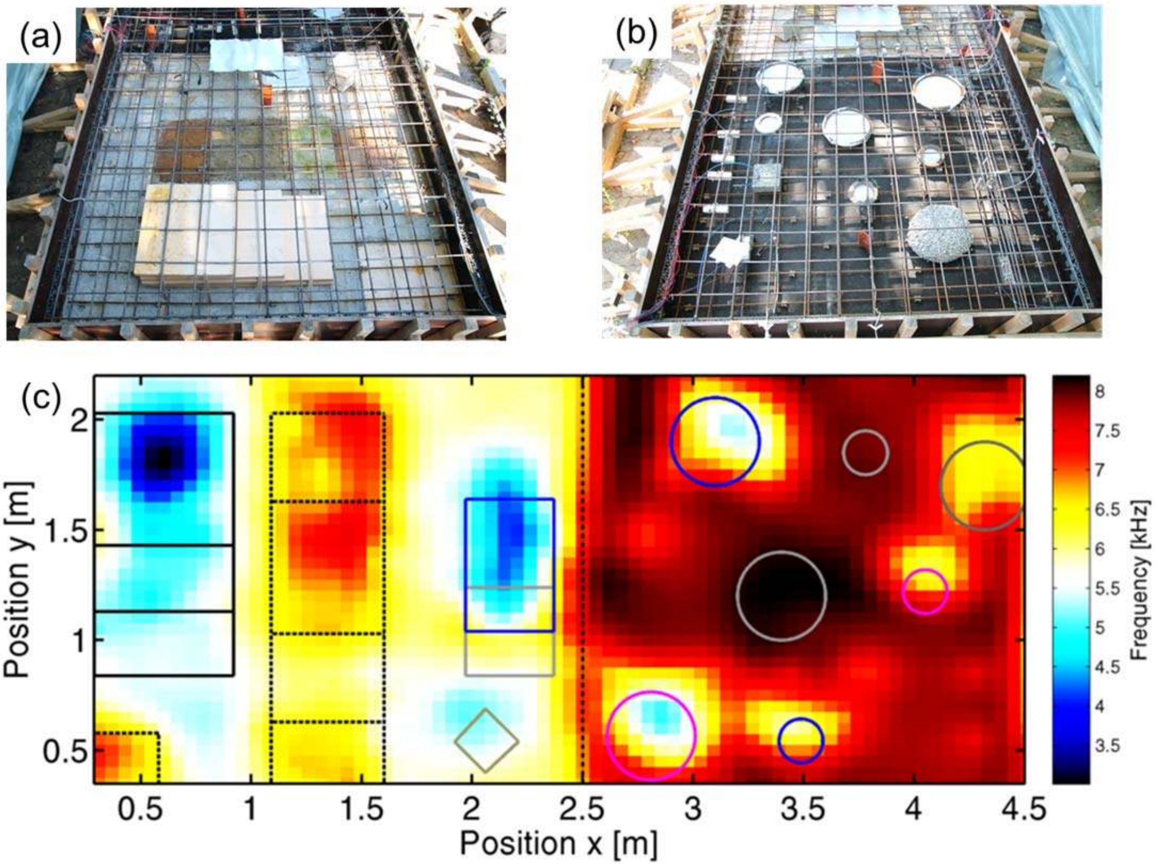

Fig. 3. Top row: Photographs of test slab with artificial defects before concrete was cast. (a) Left half of slab with reduced thickness regions, differing foundation materials and rectangular PTFE sheets. (b) Right half of the slab containing circular shaped PTFE sheets and loose gravel. This half of the slab is completely decoupled from foundation through a rubber mat. (c) Result of the scanning measurement with the prototype representing a smoothed image of dominant signal frequencies. Overlaid are designed positions of internal flaws (solid lines) and varying base materials (dashed lines).

3.2 Signal Processing

As in conventional IE data processing time domain recordings were transformed into the frequency domain by FFT (fast fourier transform) analysis. To increase oscillatory components and spectral resolution an autocorrelation was performed on windowed raw data. Samples from a time window (Tukey window) of 6 ms after initial arrival of sound waves from the impactor was passed for processing. Windowing was based on the piezo sensor mounted on the solenoid plunger acting as the trigger source and thereby providing exact information about the impact time. Resulting spectra from spatial bins containing three individual impacts were averaged. After these operations a two-dimensional smoothed imaged of the dominant signal frequency was created (Fig. 3(c)).

Most of the built in features find a clear expression in the produced scan image. As expected from IE theory, undisturbed regions of the slab, where it is completely decoupled from the foundation (right half of the slab), show a dominant frequency of 7.7 kHz ± 0.5 kHz (thickness resonance mode). Due to flexural vibrations regions above delaminated or shallow areas show lower frequency values. Also the different foundation conditions find expression in variations of the frequency readings. The described processing scheme was also applied to the following measurements.

3.3 Application of Prototype on Concrete Pavements

3.3.1 Measurement in the Vicinity of a Plate Joint

The scanner was further employed for a test measurement on a concrete pavement section where horizontal cracks were suspected along dummy joints. To gain a first qualitative insight in the behaviour of IE signals above plate joints with delamination defects a numerical simulation of wave propagation was performed. The two-dimensional model for the simulation consisted of a 20 cm thick concrete layer containing a notch and a horizontal crack spanning to both sides from the tip of the notch (Fig. 4 (a)). The resulting simulated IE data is presented in the frequency domain (Fig. 4 (b)) and compared to field data acquired with the prototype (Fig. 4 (c)). Both data sets show a dominant frequency of around 9.5 kHz and 10.5 kHz respectively in regions away from the notch. This frequency can be attributed to the thickness resonance mode and corresponds to the plate thickness of around 20 cm. The difference between simulation and field data results from different material parameters used in the simulation and potentially from deviations of the real pavement from the designed thickness. In the region around the notch both datasets show frequency values around 5 kHz. This observation can be interpreted as flexural vibrations of delaminated sections around the notch. Based on the qualitative agreement between simulation and field data it can be concluded that the pavement section is affected by a delamination in the vicinity of the notch and this defect can be imaged with the prototype scanner.

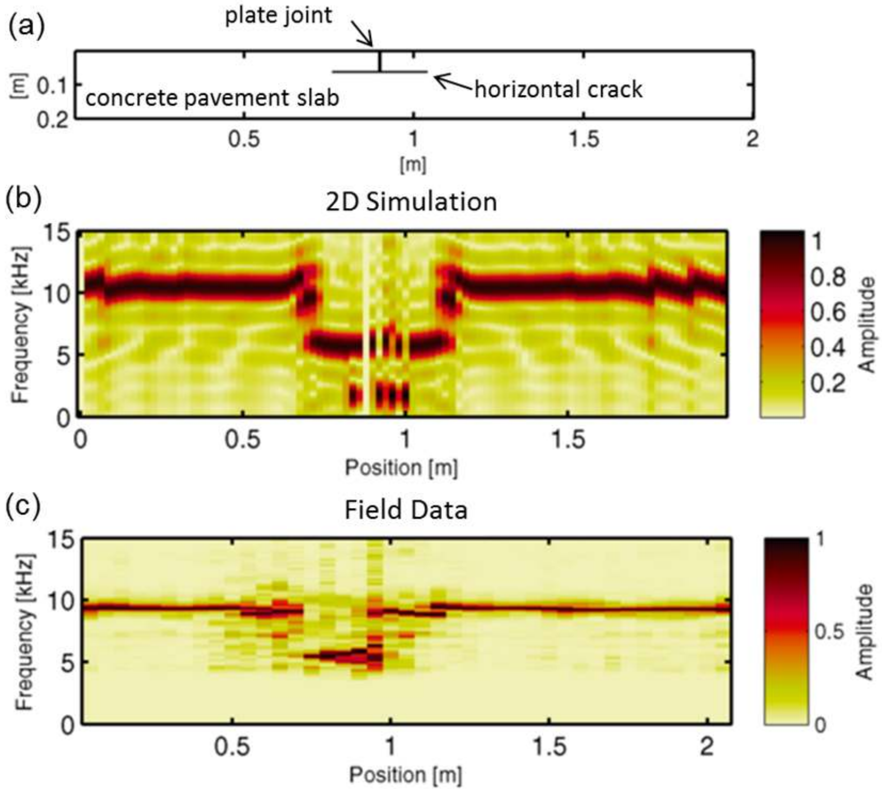

Fig. 4. (a) Two dimensional geometry model of concrete pavement slab with plate joint and horizontal crack. (b) Simulated impact-echo scan result. (c) Test result on a real pavement section in the vicinity of a joint.

3.3.2 Measurement on a Disassembled Slab Section

Another testing scenario was available in the form of a disassembled slab section of a highway concrete pavement with visible delamination defects (Fig. 5). The front end of the 30 cm thick slab (which was near a joint when the slab was still in operating condition) shows a distinct horizontal crack (Fig. 5 (a)). A direct observation of the extension of the crack along the plate was not possible. The other end of the slab shows no apparent damage (Fig. 5 (b)). A line scan along the centre of the slab was performed with the prototype (Fig. 5 (c)). The frequency image towards the sound part of the slab shows values around 7 kHz. This value is within expectation by IE theory for a 30 cm thick slab. The frequencies at scan positions with the obvious damage significantly drop to lower frequencies. This behaviour can be attributed to a decrease of the elastic modulus in the cracked region and to a flexural vibration of slab sections above the horizontal crack. The measurement results allow an estimation of the extension of the damaged region (approximately 70 cm from the front edge of the slab).

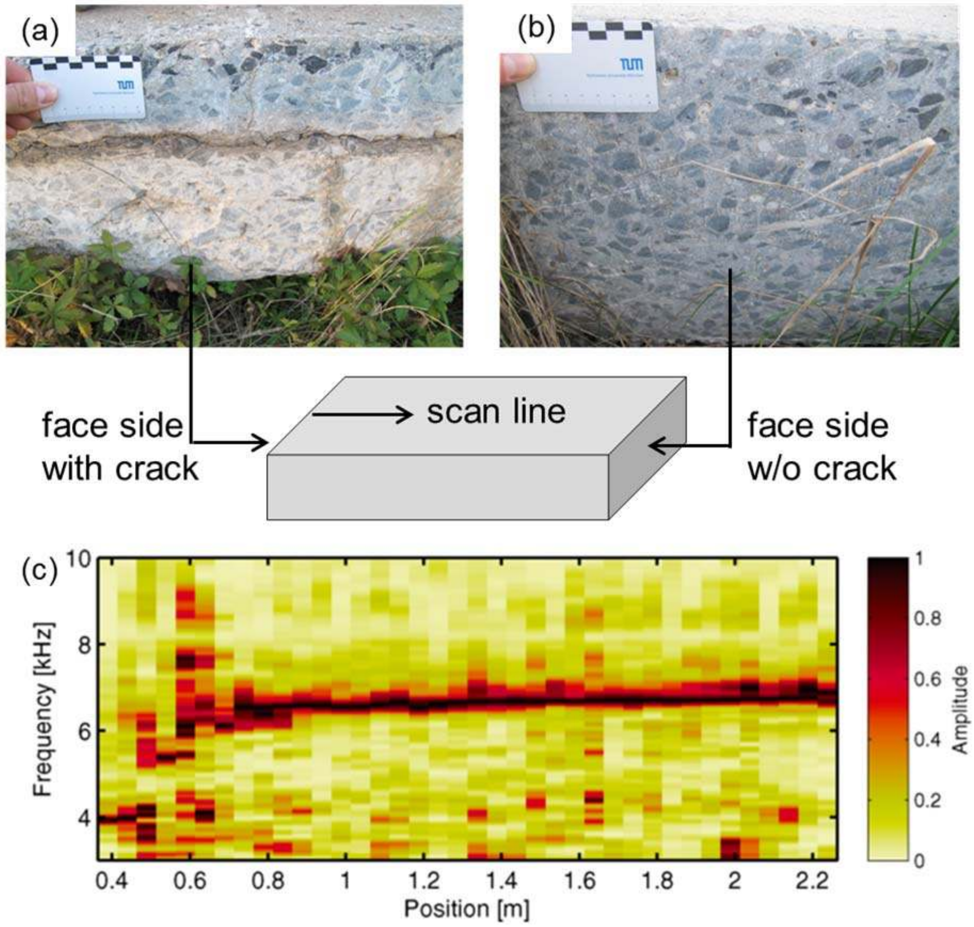

Fig. 5. Top row: photographs of lateral sides of a disassembled concrete slab with (a) and without (b) apparent damage. (c) Measurement result. The scan line starts at the damaged side of the slab and extends towards the side with no visible damage.

4. Summary and Conclusions

A new concept for acoustic scanning of large concrete surfaces was evaluated with practice-oriented measurements. Making use of an optimized acoustic sensor the developed prototype device successfully imaged internal details and flaws of concrete structures by recording air-coupled elastic waves and structural vibrations. The innovative character of the prototype lies in the combination of efficient automated impact generation and a new approach in air-coupled sensing with a microphone array. The array sensor takes advantage of the spatial extent of radiated waves carrying relevant information about the structure properties. While disturbing sound sources are recorded with low sensitivity, the array sensor has its greatest sensitivity to plane wave fronts radiated from the surface under test. With this sensing concept problems of signal degradation in air-coupled impact-echo measurements due to interference of airborne impact noise, ambient noise and radiating elastic waves are eased off.

Key advantage of the proposed system is the applicability to tasks where an efficient testing procedure is necessary in terms of scanning speed and sensitivity to the examination target. Therefore, the presented approach is well suited for detection of delaminations or horizontal cracking in concrete pavements. In this application case vast areas need to be evaluated. Other known methods like contact ultrasonic testing or ground penetrating radar have difficulties either in sensitivity to the relevant type of damage or operational restrictions like slow testing speeds. The proposed system is therefore a promising candidate for routine NDT operations on concrete pavements. Further optimizations of the prototype concerning optimization of scanning speed, enlargement of scan width, sensitivity, data processing and result presentation are in progress.

Acknowledgments

We acknowledge the support of the German Federal Highway Research Institute (Bundesanstalt für Straßenwesen). This presented work is conducted on behalf of the Federal Ministry of Transport and Digital Infrastructure, under grant No.08.238.
The author is solely responsible for the content.
We would like to express thanks to Tremba GmbH for valuable contributions in developing the impact source.

References

[1] Zhu, J.Y. and J.S. Popovics, *Imaging concrete structures using air-coupled impact-echo.* Journal of Engineering Mechanics-Asce, 2007. 133(6): p. 628-640.
[2] Gibson, A., N. Ryden, and J.S. Popovics. *Advances in air-coupled lamb wave scanning*. in *Proceedings of the Symposium on the Application of Geophyics to Engineering and Environmental Problems, SAGEEP*. 2007. Denver, CO, USA.
[3] Lu, Y., et al., *A mobile acoustic subsurface sensing (MASS) system for rapid roadway assessment.* Sensors (Switzerland), 2013. 13(5): p. 5881-5896.
[4] Ryden, N., M.J.S. Lowe, and P. Cawley. *Non-contact surface wave testing of pavements using a rolling microphone array*. in *NDTCE'09, Non-Destructive Testing in Civil Engineering* 2009. Nantes, France.
[5] Park, C.B., R.D. Miller, and J. Xia, *Multichannel analysis of surface waves.* Geophysics, 1999. 64(3): p. 800-808.
[6] Sansalone, M.J. and N.J. Carino, *Impact-echo: A method for flaw detection in concrete using transient stress waves.* National Bureau of Standards, 1986. Rep. No. NBSIR, 86-3452.
[7] Carino, N.J., M. Sansalone, and N.N. Hsu, *A Point Source-Point Receiver, Pulse-Echo Technique for Flaw Detection in Concrete.* Journal of the American Concrete Institute, 1986. 83(2): p. 199-208.
[8] Gibson, A. and J.S. Popovics, *Lamb wave basis for impact-echo method analysis.* Journal of Engineering Mechanics-Asce, 2005. 131(4): p. 438-443.
[9] Oh, T., J.S. Popovics, and S.H. Sim, *Analysis of vibration for regions above rectangular delamination defects in solids.* Journal of Sound and Vibration, 2013. 332(7): p. 1766-1776.
[10] Tinkey, Y. and L.D. Olson. *Vehicle-Mounted Bridge Deck Scanner, Final Report for Highway IDEAProject 132*. 2010, Transportation Research Board.
[11] Groschup, R. and C. Grosse, *MEMS Microphone Array Sensor for Air-Coupled Impact-Echo.* Sensors, 2015. 15(7): p. 14932-14945.
[12] Groschup, R. and C.U. Grosse. *Enhancing Air-Coupled Impact-Echo with Microphone Arrays*. in *Proceedings of the 2015 International Symposium on Non-Destructive Testing in Civil Engineering, NDT-CE*. 2015. Berlin.