

Signal Processing for Air-Coupled Impact-Echo using Microphone Arrays

Daniel ALGERNON¹, Hardy ERNST¹, Klaus DRESSLER¹

¹ SVTI Swiss Association for Technical Inspections, Nuclear Inspectorate, Switzerland

Contact: daniel.algernon@svti.ch

Abstract

Impact-echo is an acoustic method for non-destructive testing of concrete structures. It is based on the use of elastic waves created by the impact of a small steel sphere on the concrete surface and analysis of multiple reflections in the frequency domain. In combination with imaging techniques cross-sectional views of the structure can be obtained.

Conventional sensors need to be pressed against the surface at each measurement position and lifted up to be moved, which makes field testing quite time-consuming. Furthermore, rough concrete surfaces make it hard to achieve good coupling. Therefore, the use of air-coupled microphones instead of contact sensors is often seen as an attractive and promising alternative. However, in practical applications noise from the environment and especially impact noise from the steel sphere itself often make the use of microphones very difficult. In previous studies mechanical barriers have been used to shield the microphone against acoustic interference. This paper presents a technique based on signal processing algorithms in combination with arrays of two or more microphones, thus minimizing the interfering signal components. This makes the system resistant against acoustic noise caused by motors or wheels when using systems in motion, thus providing the basis for a significant increase in measurement speed compared to systems using conventional contact transducers. As no coupling is necessary, measurements are much less dependent on the roughness of the measurement surface.

Keywords: Impact-echo, microphones, air-coupled, signal processing, concrete.

1 Introduction

1.1 Impact-Echo

Impact-echo (IE) has been successfully used for inspection of concrete structures [1]. Its most common applications are thickness measurements of components that are accessible only from one side as well detection of delaminations. Furthermore, impact-echo is used to locate tendon ducts in post-tensioned concrete structures and, when possible, to detect voids within the grout of the ducts.

IE is based on the use of multiple reflections of elastic stress waves (longitudinal waves) generated by the elastic impact of a small steel sphere (diameter: 10 mm or smaller) on the concrete surface [2]. The waves propagate through the material and are reflected at the backwall or by a flaw in the concrete. The recorded waveforms are transformed into the frequency domain (Fast Fourier Transform (FFT)) to make the multiple reflections become apparent as distinctive peaks. The reflector depth can be calculated from the measured frequency, provided that the wave velocity is known:

$$2d = c_L \cdot T = \frac{c_L}{f} \Leftrightarrow \boxed{d = \frac{c_L}{2f}} \quad (1)$$

c_L : long. wave velocity
 d : depth of reflector
 T : time of flight
 f : frequency

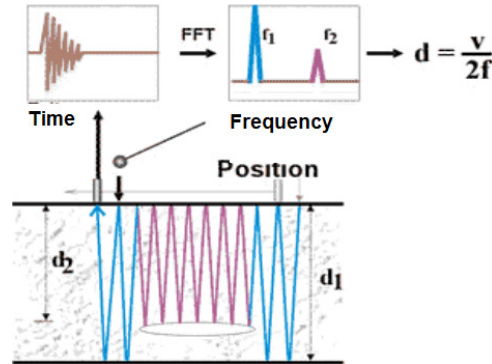


Figure 1: Principle of Impact-Echo(IE)

(SOURCE: BAM – Federal Institute for Materials Research and Testing, Germany)

Impact-Echo is mostly suitable for wider components such as slabs. On components of rather compact dimensions or complex geometry, boundary effects can cause severe artifacts.

1.2 B-Scan Imaging

Although impact-echo was originally designed as a single-point measurement method [4], i.e. the acquired waveforms were analyzed individually, it is nowadays used as a scanning method in combination with the so-called B-scan imaging technique [1,3]. Measurements are collected along a grid consisting of parallel scan lines with equidistant measurement points. At every position of the grid a waveform is collected and the frequency spectrum is determined and plotted based on a color map, i.e. colors are assigned to the amplitudes of the spectrum. By aligning the color-mapped frequency spectra next to each other along the scan line, an image of amplitude as a function of frequency and measurement position is obtained. Based on the relation between frequency and depth given by Equation (1), this image can be interpreted as a cross-sectional view of the structure along the scan line. In accordance with the terminology used in ultrasonics, this image is referred to as a (freq.-) B-scan, whereas a single frequency spectrum is referred to as a (frequency-) A-scan.

The spacing between the points along the scan line, i.e. the grid density, provides the resolution of the image along the horizontal (position) axis.

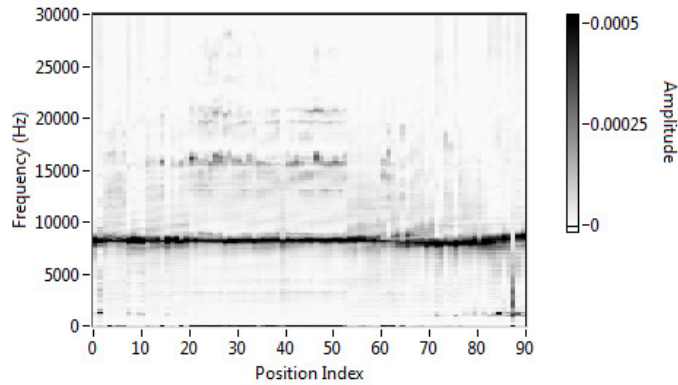


Figure 2: Example of an impact-echo (frequency-) B-scan. At every measurement position the frequency spectrum is plotted in grey scale. Aligning the frequency spectra next to each other along the scan line, an image is obtained, which provides a cross-sectional view of the test object along the scan line.

1.3 Objective of Air-Coupled Impact-Echo

Impact-echo scan areas can consist of a very large number of measurement points, thus making inspections quite time-consuming. While the recorded length of a waveform itself is as low as 10 msec, the by far most time-consuming part of measurements with conventional contact sensors is the process of lifting up the sensor, moving it to the next measurement position and ensuring good coupling. This process usually takes not less than 5-10 sec per measurement position. Furthermore, the application of contact sensors requires rather smooth surfaces to achieve sufficient coupling.

Air-coupled microphones [5]-[12] are seen as a promising alternative to conventional contact sensors. Microphones are not only much less dependent on the surface condition of the test object, but can also scan the inspection area in continuous motion (e.g. mounted on a small cart), which has potential to increase the measurement speed significantly.

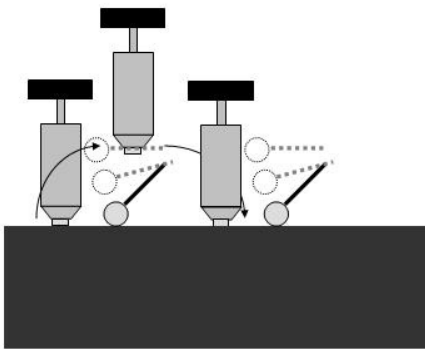


Figure 3: Time-consuming scanning using conventional contact sensors. The sensor needs to be raised between the measurement positions and coupled to the surface.

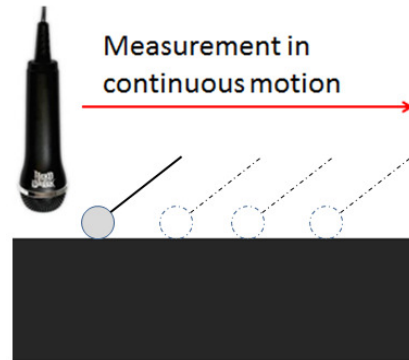


Figure 4: Goal: Measurement in continuous motion using a microphone

2. Air-Coupled Impact-Echo

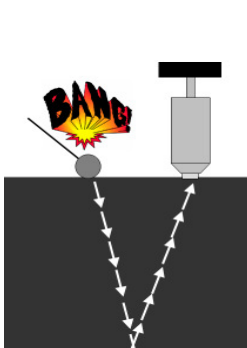
2.1 Microphones vs. Contact Sensors

Especially for measurements within the lower frequency range up to 12 kHz microphones (Figure 5) provide a very promising and cost-efficient solution for impact-echo data acquisition [5,6,7,8,9,10,11,12].

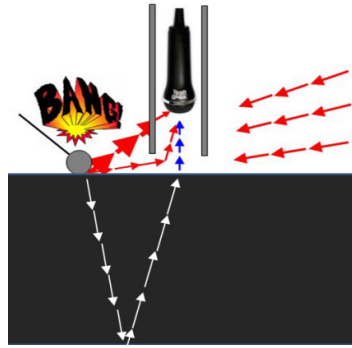


*Figure 5: Example of microphones used for IE.
Left: simple capacitor microphone (50 - 16000 Hz),
Right: high precision microphone (4 - 20000 Hz).*

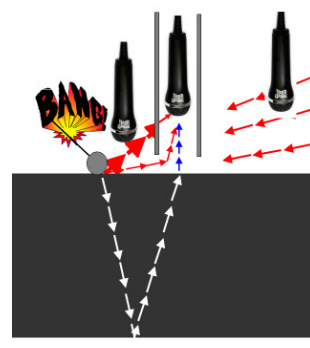
However, in practical applications noise from the environment and especially the impact noise from the steel sphere itself often make the use of microphones very difficult.



*Figure 6:
Conventional IE measurement
using a contact sensor*



*Figure 7:
IE measurement using a
shielded microphone*



*Figure 8:
IE measurement using a
combination of a shielded
microphone and additional
unshielded microphones
(microphone array).*

In general, such interferences can be reduced using an acoustic shield around the microphone. However, especially when a microphone is mounted on a cart or scanner for continuous scanning, this as well as the unavoidable gap between the shield and the surface of the test object will result in additional noise.

These challenges can be overcome by utilizing a combination of microphones aligned in an array as well as application of the respective signal processing techniques [13], which will be introduced here.

2.2 Microphone Arrays and Signal Processing

The use of an acoustic shield alone is limited in practice when noise from the environment and especially noise caused by the scanner or cart have to be taken into account. The use of a

microphone combination as well as signal processing techniques to increase the effect of the acoustic shield is described in the following. This approach is based on a comparison between the signals obtained with and without the shield in the time as well as in the frequency domain.

The scheme given in Figure 9 shows an example of a possible array of the microphones. In this setup only one microphone (1) is shielded. An unshielded microphone (2) is placed next to the shielded one (1). The impact is applied close to microphones (1) and (2). Further unshielded microphones ((3), (4), (5),... (n)) are placed at increasing distances to (1) and (2).

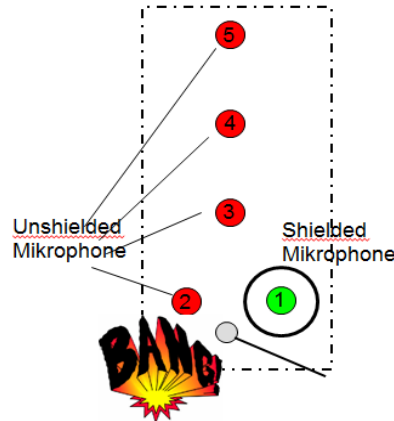


Figure 9: Example of a possible array alignment of microphones, consisting of a shielded microphone (1) and four unshielded microphones (2-5).

By comparing the normalized frequency spectra obtained for the signals recorded by microphones (1) and (2) a significant increase in the signal-to-noise ratio can be achieved already. This is based on the fact that the IE signal is equally present in the signals of the shielded (1) as well as the unshielded (2) microphone, whereas the acoustic interferences are significantly higher in the signal of microphone (2).

The comparison of the waveforms in the time domain serves specifically to identify and eliminate the interference caused by the direct air wave of the impact noise. Therefore, the microphones are placed at different distances to the impact point in order to achieve a different time shift of the interfering component against the actual IE component in the signals. Using a cross-correlation of the collected waveforms, the interfering signal of the direct air wave (high amplitude) can be extracted and then subtracted from the original waveform obtained from microphone (1). The resulting signal can then be transformed into the frequency domain.

3. Demonstration

The procedure described above has been applied to test blocks.

Figure 10 shows a concrete wall with a thickness of 30 cm. Figure 11 shows the B-scans of scan lines consisting of 50 points and a spacing of 20 mm between the points. The B-scan on the left was acquired using a microphone array as described above, the B-scan on the right was obtained using a conventional contact sensor and serves just as a reference.

The B-scan obtained from the microphones shows good correlation with the reference. The backwall is clearly visible and even geometrical effects, i.e. reflections at the boundaries appearing as regular patterns, can still be identified.



Figure 10: Concrete wall of 30 cm in thickness..

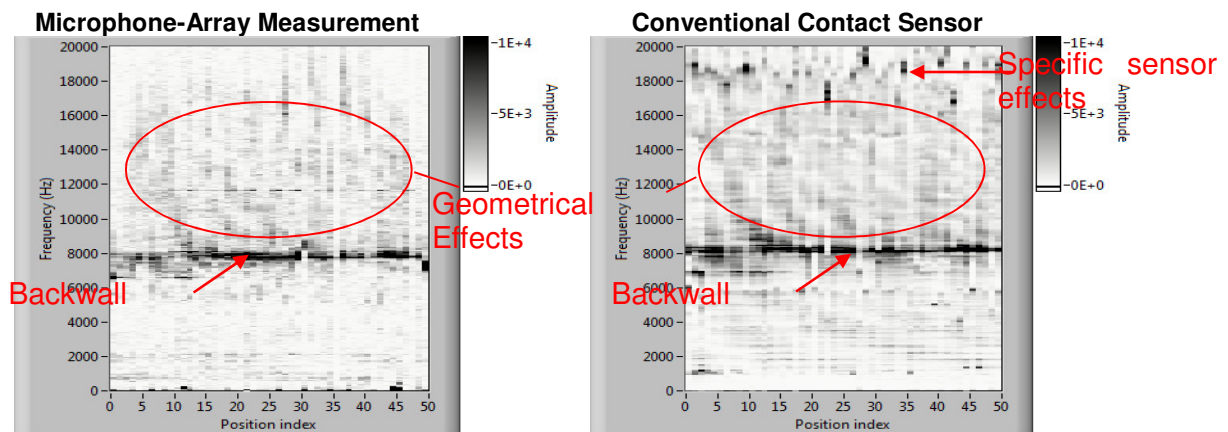


Figure 11: Comparison of B-scans obtained from microphone-array measurements (left) and conventional contact sensors (right). The backwall as well as the significant geometrical effects are clearly visible. The sensor specific effects occurring with the conventional contact sensor at approximately 19 kHz do not occur in the B-scan obtained with the microphone array.

Figure 12 shows a schematic picture of a test block at the Federal Institute for Materials Research and Testing (BAM) in Berlin, Germany. The dimensions of the block are approximately 2.00/1.50/0.25 m. There are three partially grouted tendon ducts embedded in the concrete. Microphone measurements were taken along the front surface (2.00 m by 1.50 m) crossing the ducts. The B-scan of a 160 cm long scan line with a spacing of 20 mm between the consecutive measurement points is shown in the lower section of Figure 12. The backwall at approximately 8000 Hz as well the position of the ducts revealed by a drop in frequency can be seen very clearly. The data quality, i.e. the signal-to-noise ratio, is good and totally comparable to that obtained by contact sensors.

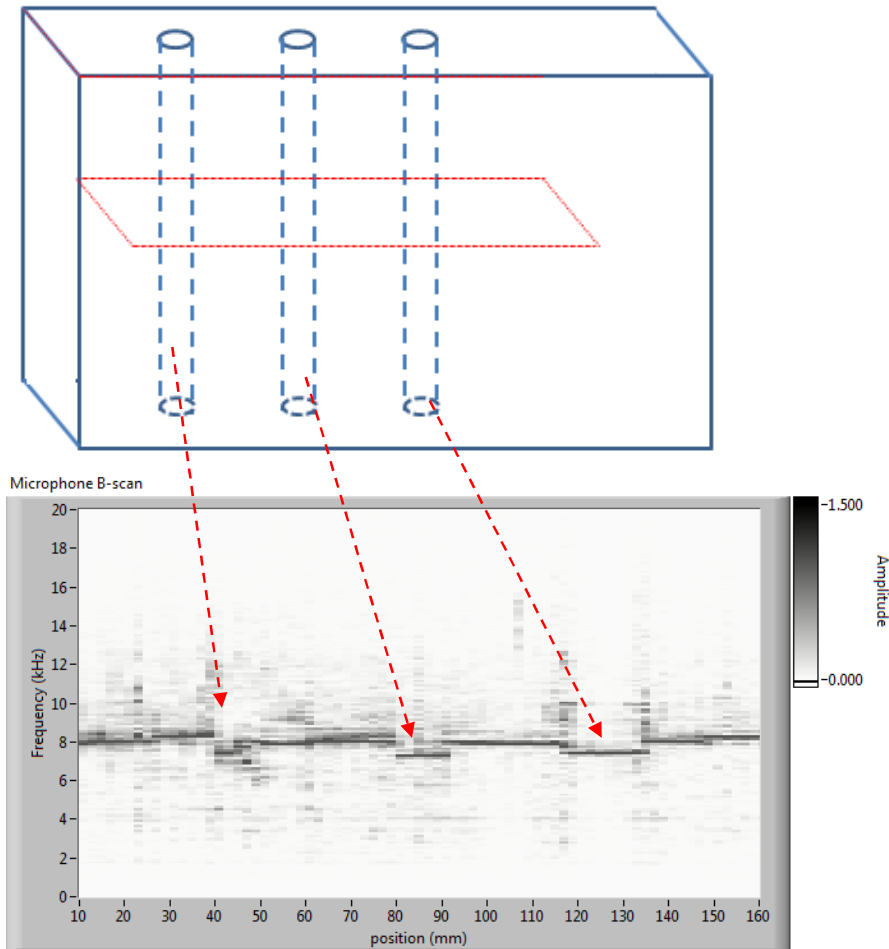


Figure 12: B-scan of microphone measurement on test block with three partially filled tendon ducts embedded in the concrete. The apparent backwall shift towards lower frequencies reveals the position of the ducts.

4. Conclusion

Microphones have proven to be a good alternative to conventional contact sensors. Although they are generally quite sensitive to acoustic interferences due to environmental as well as mechanical noise, these challenges can be overcome by using an acoustic shield, a combination of microphones (array) and signal processing techniques. This provides a basis for measurements in continuous motion and therefore a significant increase in measurement speed. Furthermore, since no contact is necessary, microphones are less dependent on the surface condition of the test object.

Acknowledgments

The authors would like to thank BAM, division VIII.2 (Federal Institute for Materials Research and Testing, Berlin, Germany) for their friendly support in providing their test blocks for conduction of the experiments.

References

1. Wiggenhauser, H. Duct inspection using scanning impact-echo. International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE), Berlin, Germany, September 2003, (DGZfP, Berlin, 2003), Proceedings on BB 85-CD, V101.
2. Sansalone, M.J. and Streett, W.B., 1997, Impact-echo – Nondestructive Evaluation for Concrete and Masonry, Bullbire Press, Ithaca, NY.
3. Tinkey, Y., Olson, L. & H. Wiggenhauser: Impact Echo Scanning for Discontinuity Detection and Imaging in Posttensioned Concrete Bridges and Other Structures. *Materials Evaluation* 63 (2005) 1, pp. 64-69.
4. Carino, N. J., Sansalone, M. and Hsu N. N., 1986, A Point-Source Receiver, Pulse-Echo Technique for Flaw Detection in Concrete: *ACI Materials Journal*, 83, 199–208.
5. Zhu, J., Non-Contact NDT of Concrete Structures Using Air-Coupled Sensors. Dissertation, University of Illinois, Urbana-Champaign, 2005.
6. Zhu, J. and J. Popovics: Imaging Concrete Structures Using Air-Coupled Impact-Echo. *Journal of Engineering Mechanics*. 133, 628 (2007).
7. Kee, S.H., Fernández-Gómez, E., and Zhu, J., “Evaluating surface-breaking cracks in concrete using air-coupled sensors”, *ACI Materials Journal*, in press, 2011.
8. Zhu, J., and Popovics, J.S., “Air-Coupled Impact-Echo Imaging of Concrete Structures,” 6th International Symposium on NDT in Civil Engineering (NDT-CE 2006), Aug. 2006, St.Louis, MO.
9. 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.
10. Gibson, A. and Popovics, J. S., 2005, Lamb Wave Basis for Impact-Echo Method Analysis: *ASCE Journal of Engineering Mechanics*, 131, 438-443.
11. 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.
12. Popovics, J. S. and Zhu J., 2006, Air-coupled impact-echo imaging of concrete decks and slabs: in Proceedings of the 2006 Highway Geophysics Conference, edited by N. Anderson. The University of Missouri-Rolla, Rolla Mo.
13. Algernon, D., Ernst, H. and K. Dressler: Signalverarbeitungsmethoden zur Anwendung des Impact-Echoverfahrens mit Luftankopplung in Array-Anordnung. DGZfP-Jahrestagung 2011.