ASSESSMENT OF STRUCTURAL CONCRETE COMPONENTS USING AIR-COUPLED IMPACT-ECHO

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ABSTRACT

The impact-echo method is based on frequency analysis of elastic waves generated by the elastic impact of a small steel sphere on the surface of a concrete structure. After having been in use for the assessment of civil structures for many years, it has nowadays been increasingly applied to concrete components of nuclear facilities. Especially the enhanced interpretability obtained from imaging techniques applied to impact-echo data has significantly contributed to its successful application.

The resolution of the images obtained corresponds directly to the density of the measurement grid. On the other hand, a fine grid can make the inspection very time-consuming when conventional contact sensors are used that need to be lifted up and moved from one measurement point to the next. Therefore, the use of air-coupled (non-contact) microphones, which can be moved along the scan area in continuous motion, provides a promising alternative. While noise from the environment and especially the impact noise of the steel sphere itself has made practical applications quite challenging so far, the present paper demonstrates how this difficulty can be overcome by signal processing algorithms in combination with arrays of two or more microphones. This provides the basis for time-efficient scanning of large concrete surfaces in order to detect flaws such as delamination, minor thickness or air voids, locate structural elements such as tendon ducts or help in determining material properties. As no coupling is necessary, measurements become very little dependent on the roughness of the measurement surface.

INTRODUCTION

In terms of ageing management of concrete components of nuclear power plants, advanced nondestructive testing (NDT) methods are becoming increasingly important. Especially regarding the extension of the service life of nuclear plants, more detailed and quantitative information about the structural condition of also the safety related concrete components is needed, which can be provided by such methods. Besides the containment wall, which might have attracted the greatest attention so far, there are further safety related concrete components, where substance failure could lead to consequential damage or active waste contaminants, such as fuel cooling ponds, supporting structures, crane platforms, etc. [1].

Concrete in general is a rather challenging material for the application of especially acoustic NDT methods such as ultrasonics. A significant characteristic of concrete is its porosity. Ultrasonic probes in the frequency range of several megahertz as they are used on metals are generally not used for concrete, since the resulting short wavelengths would cause the waves to be severely scattered at the air voids and interfaces between the particles. Furthermore, the relatively large thickness of typical concrete components requires probes and methods with high penetration depth, as for example the impact-echo method.

Impact-Echo

Impact-echo is an acoustic NDT method used for inspection of concrete structures [3]. It is based on the analysis of multiple reflections of an elastic wave generated by the elastic impact on the surface of a concrete component [4, 6]. The wave propagates through the material and is reflected multiple times at the backwall or flaws such as delaminations parallel to the surface. The reflections are measured by a sensor placed adjacent to the impact point and recorded over time. For analysis the recorded waveforms are transformed into the frequency domain using a 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:

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

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

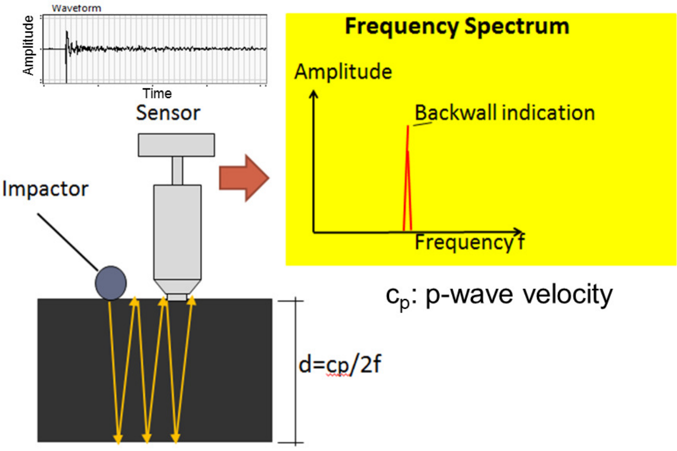


Figure 1: Principle of Impact-Echo(IE)

Since measurements on components of compact dimensions or with a complex geometry will be interfered by boundary effects, impact-echo is mostly suitable for wider components such as slabs. Typical applications are thickness measurements of components that are accessible from only 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 [3, 5].

B-Scan Imaging for Impact-Echo

Impact-Echo has originally been used as a single-point measurement method, i.e. the acquired waveforms are analyzed individually. Nowadays, the application of B-scan imaging techniques [5, 6] as known for ultrasonics, is becoming more common and has definitely improved the interpretability of impact-echo data.

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 (frequency-) 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.

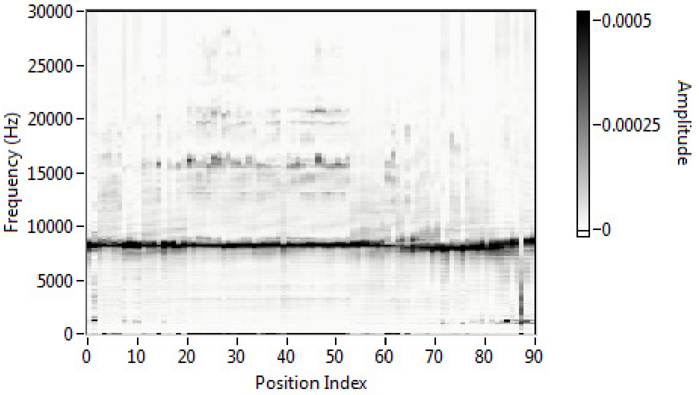


Figure 2: Example of an impact-echo (frequency-) B-scan. At every measurement position the frequency spectrum is plotted in grey scale. Aligning the frequency spectra next to each other along the scan line, an image is obtained, which provides a cross-sectional view of the test object along the scan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

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 [7 to 14] 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.

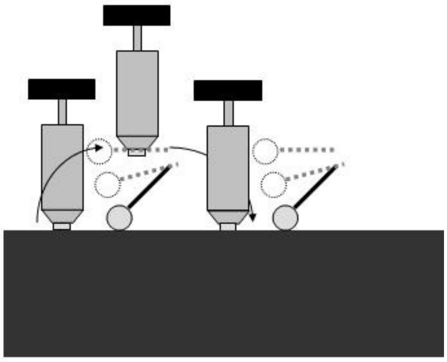


Figure 3: Time-consuming scanning using conventional contact sensors. The sensor needs to be raised between the measurement positions and coupled to the surface**.**

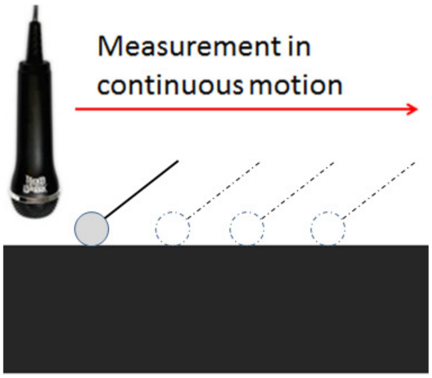


Figure 4: Goal: Measurement in continuous motion using a microphone

AIR-COUPLED IMPACT-ECHO

Microphones

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 [2,7,8,9,10,11,12,13,14].

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 (Figure 6) itself often make the use of microphones very difficult [2].

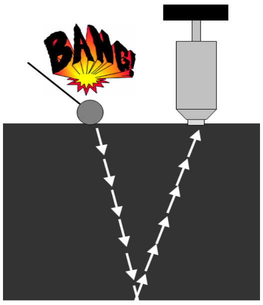


Figure 6: Conventional IE measurement using a contact sensor

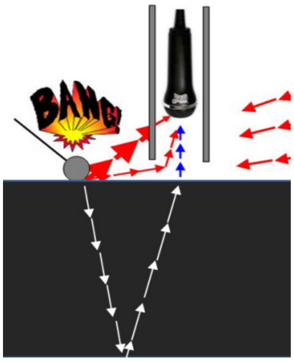


Figure 7: IE measurement using a shielded microphone

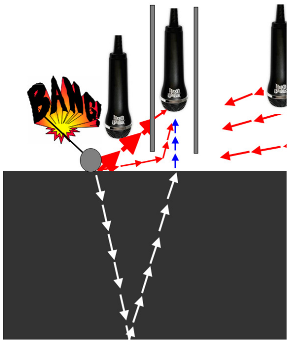


Figure 8: IE measurement using a combination of a shielded microphone and additional unshielded microphones (microphone array).

In general, such interferences can be reduced using an acoustic shield around the microphone (Figure 7). 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 [2].

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 [15].

This approach is based on a comparison of the signal obtained from the shielded microphone with signals obtained from unshielded microphones. Those components of the signal or the frequency spectrum respectively that are reduced by the shield will be set to zero. Since it is just the difference between the respective signals that is analyzed here, the shield does not need to be perfect, it just needs to be enough to cause a significant difference compared to the signal obtained from the unshielded signal. That makes the method suitable for practice since noise from the environment or from the continuous motion will affect the measurement by far less than it would be the case for a single microphone even if it is shielded [2].

DEMONSTRATION

The procedure described above has been applied to test blocks [2].

Figure 9 shows a concrete wall with a thickness of 30 cm. Figure 10 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 9: Concrete wall used as test object..

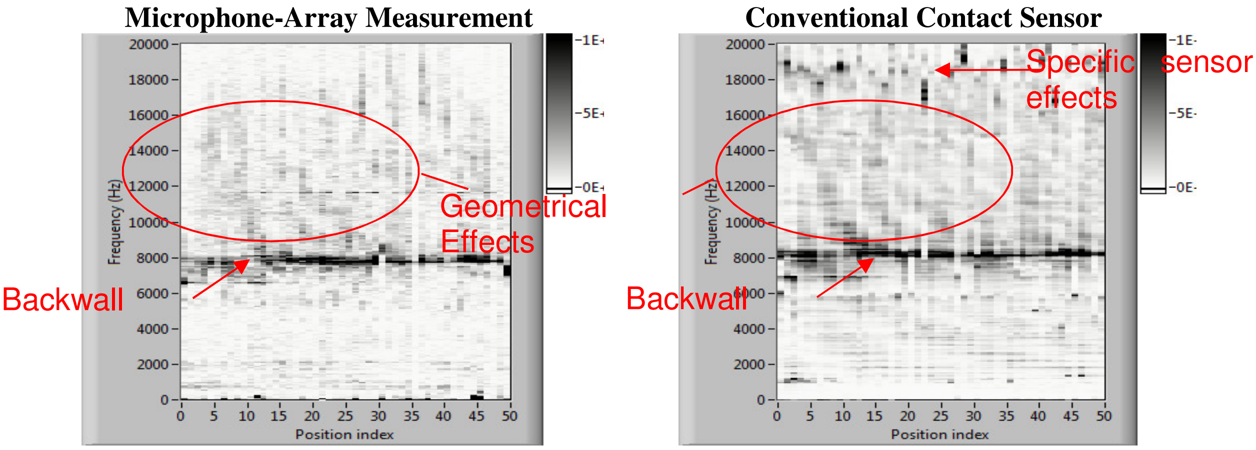


Figure 10: Comparison of B-scans obtained from microphone-array measurements (left) und conventional contact sensors (right). The backwall as well as the significant geometrical effects are clearly visible. The sensor specific effects occurring with the conventional contact sensor at approximately 19 kHz do not occur in the B-scan obtained with the microphone array.

Figure 11 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 11. 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 [2].

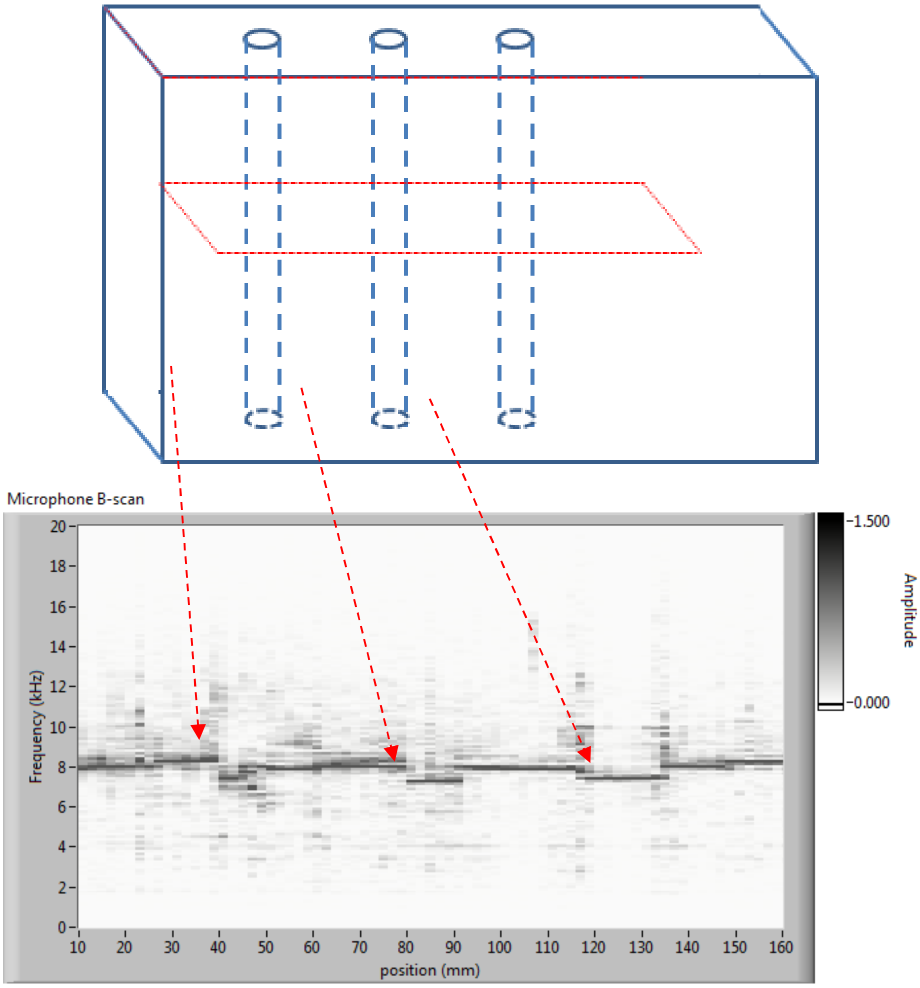


Figure 11: B-scan of microphone measurement on test block with three partially filled tendon ducts embedded in the concrete. The apparent backwall shift towards lower frequencies reveals the position of the ducts.

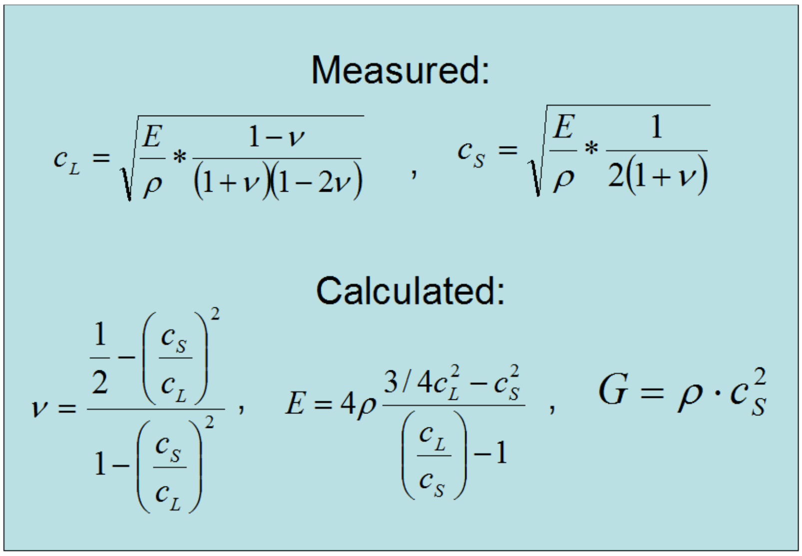
COMBINATION WITH SHEAR WAVE ULTRASONICS FOR DETERMINING ELASTIC PARAMETERS

Especially in combination with shear wave ultrasonics, impact-echo can be used to determine the elastic parameters [16, 17].

Since impact-echo is based on the use of longitudinal waves, the longitudinal wave velocity c_p (also: c_L) can be determined if the thickness of the component is known for a specific position. In the same way, the shear wave velocity can be determined using shear wave ultrasonics (Figure 12).

Figure 12: Ultrasonic pulse-echo device Eyecon using an array of dry coupled shear wave probes.

Based on these two parameters, the Poisson's ratio ν can be calculated as shown in Figure 13. Furthermore, if the density ρ is known, the modulus of elasticity E and the shear wave modulus G can be determined too [17].



Measured:

$$c_L = \sqrt{\frac{E}{\rho} * \frac{1-\nu}{(1+\nu)(1-2\nu)}} \quad , \quad c_S = \sqrt{\frac{E}{\rho} * \frac{1}{2(1+\nu)}}$$

Calculated:

$$\nu = \frac{\frac{1}{2} - \left(\frac{c_S}{c_L}\right)^2}{1 - \left(\frac{c_S}{c_L}\right)^2} \quad , \quad E = 4\rho \frac{3/4 c_L^2 - c_S^2}{\left(\frac{c_L}{c_S}\right) - 1} \quad , \quad G = \rho \cdot c_S^2$$

Figure 13 – Summary of the equations to calculate Possion's ratio, modulus of elasticity and shear modulus from the longitudinal and shear wave velocity, which can be measured with impact-echo and ultrasonic-echo.

CONCLUSION

Impact-echo can be applied very efficiently by means of microphone arrays in combination with signal processing algorithms. This provides a basis for relatively fast measurements in continuous motion. Since the sensor does not need to be coupled the surface, the measurement is also much less affected by the roughness of the measurement surface.

In addition, the quality of the processed microphone data is absolutely comparable with the data quality obtained from conventional sensors, i.e. the advantages of the microphone measurements can be achieved without sacrificing data quality, as it has been demonstrated.

In this setup, impact-echo can be used efficiently for thickness measurements of slab-like components, detection of ducts or planar flaws or, for measurement of the elastic parameters, especially in combination with shear wave ultrasonics.

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