Review of recent developments in ultrasonic echo testing of concrete

Ernst NIEDERLEITHINGER [1], Stefan MAACK [1], Frank MIELENTZ [1], Ute EFFNER [1],
Christoph STRANGFELD [1]

[1] Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, Germany

Contact e-mail: ernst.niederleithinger@bam.de

ABSTRACT: Ultrasonic methods are used in concrete investigations since decades. While being limited to transmission testing in the laboratory for a while, in-situ echo measurements for structural investigations and condition assessment have made their way into practical application in the past 20 years. However, several challenges remain. On one side, there are technical issues as limitations in depth of penetration, resolution and imaging capabilities. On the other side there are still gaps in validation, standardization and certification, which are limiting the applicability in condition/load capacity assessment.

This review reports a couple of developments which will help to overcome these issues. This includes technical developments as new devices which are easier to handle on site or giving a much deeper penetration depth (e.g. the LAUS device at BAM) as well as improvements in imaging by hardware update (e. g. air coupled ultrasound or coded signals) or new software (e. g. RTM imaging). To foster the application in real world projects we are as well working on standardization by developing new reference specimen with international partners which will ensure world-wide comparability of ultrasonic and other methods and quality assurance codes. Further, non-destructive methods are being used to update probabilistic models used for the reassessment of existing structures to support the structural engineer's decisions. .

1 INTRODUCTION

Ultrasonic (US) methods are used in concrete investigations since decades. While being limited to transmission testing in the laboratory for a while, in-situ echo measurements for structural investigations and condition assessment have made their way into practical application in the past 20 years. They are applied successfully in many scenarios and testing tasks as thickness measurements, localization and characterization of tendon ducts and reinforcement as well as detection of cracks and delamination. However, several challenges remain. On one side, there are technical issues as limitations in depth of penetration, resolution and imaging capabilities. On the other side there are still gaps in validation, standardization and certification, which are limiting the applicability in condition assessment and capacity calculation models.

We are reporting several developments, which are potentially capable to overcome these limitations. Section 2 reports on improvements in ultrasonic hardware made by instrument manufacturers and in academia. Section 3 shows improvements in data processing and imaging, while section 4 focuses on work on validation, standardization and quantification. Gaps and limitations are shortly discussed in each section. This review is limited to ultrasonic echo measurements (one sided access). Transmission measurements and monitoring applications are not discussed here.

2 DEVELOPMENTS IN ULTRASONIC ECHO HARDWARE

2.1 Commercial Instruments

The last two decades have seen a tremendous development in ultrasonic echo instrumentation for concrete. Most of this development is based on the invention of shear wave point contact transducers working in frequency range from 25-100 kHz. They can be combined to linear or areal arrays to increase power when working as transmitters and sensitivity when working as receivers. The use of transducer arrays prevents data loss when a single transducer lacks contact the concrete surface. At the same time, an array provides improved directionality and averaging to smooth the effect of inhomogeneity inherent to concrete.

These arrays are used in single channel instruments (one transmitting, one receiving array with e. g. 12 transducers each). More sophisticated devices, so-called linear arrays or tomographs (Figure 1), include 8 to 16 arrays each with 3 to 4 transducers, which are switched to serve as transmitter or receiver, thus allowing multiple measurements in one go. They meanwhile must be considered as the state of the art as they allow automatically varying the distance between transmitter and receiver resulting in better illumination of the interior of the structure and online imaging capabilities. However, for larger investigation areas and/or complex testing tasks, still lots of measurements must be taken and combined.

Figure 1. State of the art ultrasonic echo instruments: ACS A1040 Mira (left) and Proceq Live Array (right).

Recent developments include additional of measured data capabilities as online storage to cloud systems (but without connection to inspection databases or BIM systems yet) or full matrix capture capabilities using every single transducer as a separate unit. The use of augmented reality for display of results has been shown as well.

While the instruments described here have revolutionized the application of US testing on concrete structures and extended the range of testing problems which can be solved, there are of course still limitations. They include a penetration depth of max. 1 m in typical cases, lack of resolution for sub-cm structures and limitations in imaging complex structures (including vertical features) or diffuse damages.

2.2 Instruments used in research

For specific applications instruments have been developed based on the same type of transducers described above. The examples discussed here are dedicated to investigate massive concrete constructions beyond the limits of commercial instrumentation.

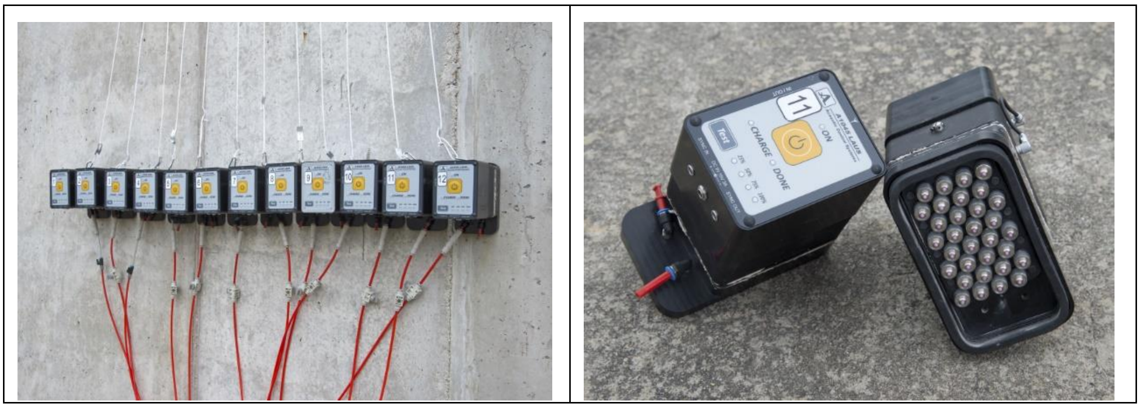

Figure 2. Deep penetration ultrasonic instrument LAUS (Wiggenhauser et al., 2017).

The deep penetration ultrasonic system LAUS (Large Aperture Ultrasonic System, Figure 2, Wiggenhauser et al., 2017, Wiggenhauser et al., 2018) has been developed to overcome the lack of penetration of commercial instruments for the inspection of massive structures. Due to an increased number of transducers (32 per array) and a larger aperture (transmitter-receiver distance) we have been able to map certain features in reinforced concrete structures up to 5 m thickness and in unreinforced concrete structures up to 8.5 m. Recently the LAUS has been used to detect cracks in engineered barriers to be used in subsurface nuclear waste repositories (Niederleithinger et al., 2019).

Figure 3 shows a result acquired on a bridge deck supported by massive girders. The investigation was carried out to locate tendon ducts and to detect potential inhomogeneities (Wiggenhauser, 2017). The LAUS array was deployed on top of the bridge and was moved in 60 cm steps inline and 10 cm across lines to produce a 3D data volume, which was processed using the InterSAFT software (see section3, Mayer & Cinta 2012). The tops of the tendon ducts in about 1.8 m depth are clearly visible, slightly less at the boundaries with less coverage. The bottom of the bridge girder (2 m depth) is visible as well, but just in between the ducts.

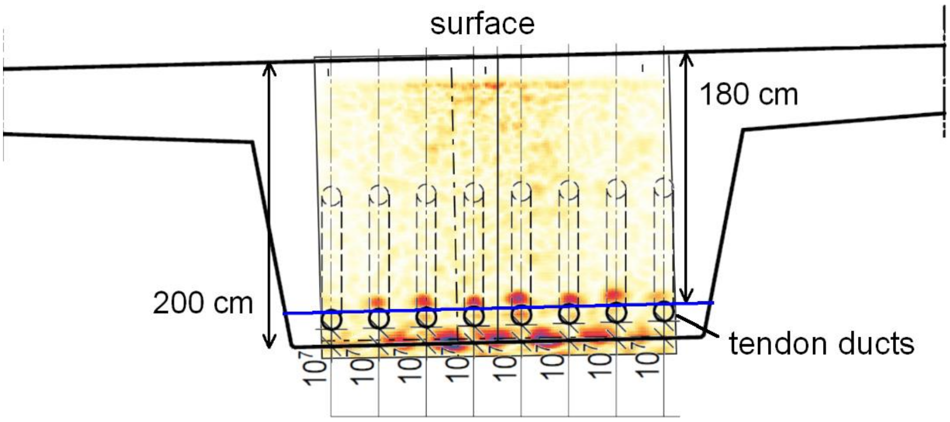

Figure 3. LAUS result from a massive bridge girder. Measured from top side to detect tendon ducts and potential damages (Wiggenhauser et al., 2017).

Still certain features are not accessible for ultrasonic echo inspection even if systems as the LAUS are used. Thus, a special probe has been developed which can be deployed in boreholes of 100 mm to 133 mm diameter. The first version shown in Figure 4 consists of 10 transducers, 5 of them coupled to be used for transmitting, the others for receiving. It is mainly used to detect cracks up to 1.8 m from the borehole. The data shown in Figure 5 were acquired in a massive concrete body built to stabilize a former salt mine.

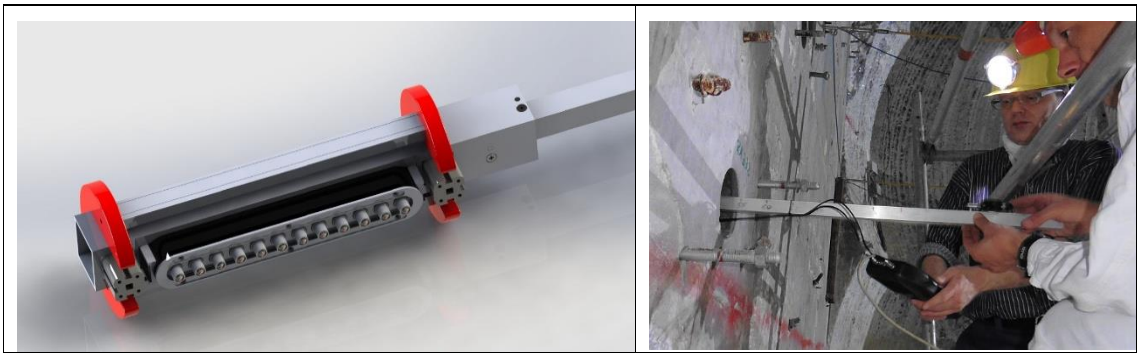

Figure 4. Ultrasonic borehole probe and deployment in a former salt mine (Niederleithinger, 2019).

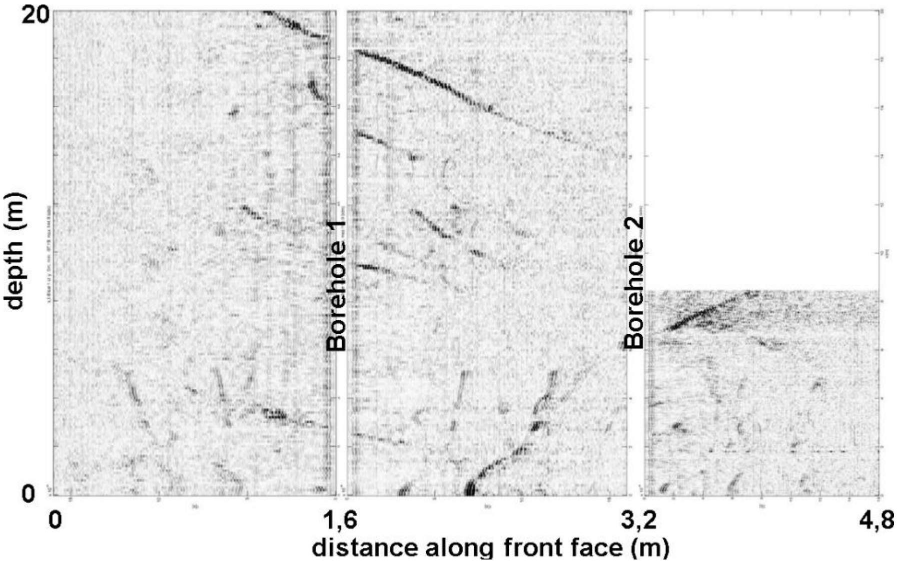

Figure 5. Combined result of borehole measurements acquired in two horizontal boreholes. Several reflectors are due to validated cracks. (Niederleithinger, 2019).

In certain applications it is hard to make contact to the surface by conventional transducers. The use of air-coupled transducers for ultrasonic echo has been introduced in research a while ago, but much less so in industrial applications (other than in transmission measurements). This is due to inherent problems due to the high impedance contrast at the interface air/concrete, requiring a high energy source, a very sensitive receiver and methods to avoid direct crosstalk. Recently, newly developed, high amplitude transducers have shown potential to be used in ultrasonic echo applications (Vössing et al., 2018). A powerful air couple source based on a fluidic oscillator is under development at BAM.

Even if these and other instruments have improved the range of applications a lot, there is still a lot of room for improvement. We (and other institutions) are working for example on the use of coded signals for image enhancement, the use of phased array technology e. g. in the borehole probe or adding more and more transducers and measurement channels to the LAUS as well as commercial ultrasonic echo instruments.

3 ULTRASONIC ECHO DATA PROCESSING AND IMAGING

In field applications, processing of ultrasonic echo data is mostly limited to time/amplitude offset correction and/or bandpass filtering. While the display of this data sets without any geometrical correction has been the standard on the past, the reconstruction of the approximately correct position and shape of reflectors has been meanwhile adopted by instrument and software manufacturers. By far, most popular is a family of methods called SAFT (Synthetic Aperture Focusing Technique). Commercial applications are using a relatively simple, but nevertheless very effective implementation (described e.g. by Choi & Popovic, 2016).

At BAM, we are using an adapted version of the SAFT algorithm implemented in the academic software InterSAFT developed by Dr. Mayer at University of Kassel (Mayer & Cinta, 2012, Mayer et al., 2015). The version currently used includes several additional modules, including true 3D processing capabilities, support for special instruments as the LAUS or nonlinear transducer arrangements as well as phase evaluation to distinguish between (in an acoustic sense) weak and hard reflectors (Mayer, 2008). The latter can be applied e.g. in studies related to voids in tendon ducts.

Certain limitations in standard SAFT imaging as the inability to map vertical reflectors can potentially be overcome by using algorithms developed for seismic oil exploration. Several NDT researchers have started experimenting with methods as Reverse Time Migration (RTM; e.g. Grohmann et al., 2015). While success has been shown in mapping previously inaccessible geometries (Figure 6), practical application was so far out of reach due to very high computer speed and memory demands. Recently, Asadollahi & Khazanovich (2018) have proposed a method to overcome this problem, potentially leading to new possibilities in ultrasonic imaging. However, these developments have still to be validated and implemented in practice.

4 VALIDATION, QUANTIFICATION AND STANDARDIZATION

Construction is performed according to developed, often updated and widely accepted standards. Unfortunately, this doesn’t necessarily apply to the inspection of structures and the application of NDT therein. In Germany the quality assurance inspection of tunnel linings for voids (“RIL-ZfP-TU”) is the only exception. There are many reasons and a long history behind that. One part of the story is the lack of validation, references and standardization.

Recently, a couple of initiatives have started to work on this issue. The German Society for Non-Destructive Testing (DGZfP) hosts a committee on civil engineering applications (“FA Bauwesen”), which has established subgroups on quality assurance of NDT-CE and education. Guidance documents are under development. At the same time, we are working on contributions to the new model code 2020 of the Fédération International du Béton (fib) to establish links between monitoring, NDT and structural design. This is supported by research on how crucial structural parameters can be described by means of quantified NDT results (including uncertainties) and how such probabilistic models can then be used for the re-assessment of existing bridges (Küttenbaum et al., 2019).

To be able to validate NDT methods for well defined testing tasks and to achieve comparable results at institutions around the world, the US Federal Highway Administration (FHWA) and BAM have developed a set of definitions and recipes for a set of reference specimen including cracks, delamination, honeycombs and corrosion, which are currently being tested at various international institutions.

5 CONCLUSIONS AND OUTLOOK

For research there is still a wide-open field to benefit from developments from seismology or classical NDT as well as to embrace emerging technologies as nonlinear ultrasound (Payan et al., 2010, Kim et al., 2018).

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