Tomographic Imaging Using Multi-Channel Low-Frequency Ultrasonic Measurement Systems

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Abstract
Multi-element ultrasonic transducer arrays open the possibility for rapid and flexible tomographic imaging systems. By electronic switching of the individual array elements, different schemes of reflection tomography and transmission tomography can be realized. This contribution firstly introduces general tomographic measurement principles to some detail. It then describes two multi-channel low-frequency ultrasonic measurement systems and their application to tomographic imaging. Both systems comprise transducer arrays in which each transducer group can be electronically switched between transmission, reception, and deactivation. Tomographic reconstruction algorithms provide three-dimensional volume imaging. The first imaging system, the reflection-tomographic FLEXUS system for concrete evaluation, incorporates a 48-element/16-channel transducer array. The array is moved by a three-axes scanner in a range of 1.0 m x 0.8 m. The collected data is online processed by a SAFT (synthetic aperture focusing technique) algorithm for reflection-tomographic volume imaging. Different SAFT variants are implemented that are optimised towards image quality or measurement speed. The second imaging system, the transmission-tomographic FLEXUS 120 system for refractory testing, includes a 60-element transmitting array and a 60-element receiving array. The two arrays are applied to opposite faces of the tested object for transmission measurements. By varying the excitation sequence and the reconstruction algorithm, different transmission-tomographic schemes in direct transmission or with angular diversity can be realized. For both imaging systems, measurement results are presented and discussed.

Keywords: Ultrasonic testing, array imaging, tomography, SAFT, civil engineering

1. Introduction

Multi-channel ultrasonic measurement systems have become a powerful means for many applications including medical diagnosis or non-destructive testing. Their advantages include rapid generation of results, coverage of relatively wide areas, and flexible configuration.

The imaging algorithms in all of these instruments rely on tomographic principles. But while most of the available phased-array instruments are well adapted to the intended detection and localization tasks, they do not represent the full potential of multi-channel tomographic imaging. The use of more advanced tomographic schemes can further improve the image quality. This is especially necessary when strongly scattering heterogeneous materials like concrete are imaged.

In this contribution, two ultrasonic measurement systems are described that make use of a number of different tomographic techniques. Both systems are based on transducer arrays in which each transducer group can be electronically switched between transmission, reception, and deactivation. This flexible approach is the basis for rapid implementation of the more complex schemes of reflection tomography and transmission tomography. Both imaging systems are described in their technical concepts, and their application is illustrated at typical measurement results. The systems, being in use for production work, show that ultrasonic tomography has the potential for detailed volume imaging even in inhomogeneous materials.

Preceding is an introduction of tomographic principles which puts the utilized tomographic techniques into a general context.
2. Tomographic measurement principles

2.1 Introduction

Tomography is the general term for an imaging method which transforms measured signals gathered at the surface of a volume into an image of the volume itself [1, 2]. The measurement signals carry information resulting from the response of the volume to some form of illumination. The term computerized tomography (CT) refers to the case where the measured signals are digitized and the image is reconstructed by a mathematical algorithm. In transmission tomography, some part of the volume is located between each of the illuminating and the measuring surface sections, whereas in reflection tomography there is no such volume. The part of the surface used for illumination and measurement is called the aperture. Its size can be restricted due to constraints by the shape of the object or the size of the measurement system. A projection contains the data set collected between the transmission aperture and the receiving aperture in transmission tomography.

In general, the image quality of the reconstruction of the volume is higher the more of the surrounding surface can be used, the more thoroughly the physical effect relates the illumination to the measurable volume response, and the more complete this physical effect is modeled by the reconstruction algorithm.

In the ultrasonic case, ultrasonic transducers both illuminate the volume by transmitting ultrasonic waves and also receive the transmitted or reflected waves. The aperture is sampled on an equidistant grid on which the transmitting and receiving transducers are located. A synthetic aperture is scanned by a single or a few transducers collecting consecutive measurements (rather than having transducers allocated to all grid points), their signals being combined in the reconstruction algorithm. Ultrasonic wave information is utilized according to the principal setup:

Reflection tomography: Ultrasonic waves backscattered within the volume are processed, using the complete signal for imaging.

Transmission tomography: Attenuation or velocity of waves transmitted through the volume are processed, using only the amplitude or the time-of-flight of the first arriving pulse for imaging.

Ultrasonic waves are diffracted and scattered at obstacles in inhomogeneous media, and the propagation velocity may vary within the volume or may depend on the propagation direction. Diffraction tomographic algorithms account for these or some of these phenomena. Straight ray tomography is easier to implement but only approximates the wave propagation. Further specializations exist for data collection – the configuration of the transmitting and receiving sensors on the aperture and their activation sequence – and data processing – the method of processing the received data. Since computed tomography is computationally intense, many algorithms have been developed in time or frequency domain, and direct or iterative variants account for anisotropic, acoustic (scalar) or elastodynamic wave propagation. Frequency domain algorithms take advantage of a re-formulation of the building equations to employ Fast Fourier Transforms. These algorithms require only a fraction of the computation time of time domain algorithms, but are generally restricted to plane and circular apertures and certain aperture configurations.
2.2 Implemented techniques

The applications at hand require flexible aperture configurations and short computation times with emphasis on detection and localization tasks in isotropic media. Hence, straight ray tomography is used with algorithms working in the time domain. The tested objects are plates or cuboids with plane apertures on a single surface or two parallel surfaces.

For one-sided access, reflection tomography was used, and transmission tomography for two-sided access. The following figures explain the implemented configurations, illustrated on two-dimensional volume sections and one-dimensional apertures.

**Reflection tomography – Synthetic Aperture Focusing Technique (SAFT)**

The simplest reflection-tomographic configuration builds on a single straight sound path between transmitter, the imaged point in the volume, and the receiver. A slight variation is the pitch-catch configuration under a fixed, small angle as depicted in Fig. 1. In the left part, a transmitter and a receiver are moved together along the aperture. In the middle part, each two transmitters and receivers, respectively, are coupled to a virtual transducer which is moved through the elements of a transducer array by appropriate cycling. The Synthetic Aperture Focusing Technique (SAFT) [3] is employed as reconstruction algorithm which is equivalent to a backpropagation in the time domain.

**Reflection tomography – Combinational Synthetic Aperture Focusing Technique (C-SAFT)**

The most complete reflection-tomographic configuration for single transducers is shown in Fig. 1, right. At each cycle of the data capture, a single transducer is transmitting and all other transducers are receiving, either one after the other or all at the same time, but independently. The cycle is repeated for all transmitting positions. In terms of reflection tomography, this scenario corresponds to a pitch-catch configuration under a limited number of different angles. Reconstruction is done using the Combinational Synthetic Aperture Focusing Technique (C-SAFT) [4, 5], also called Sampling Phased Array (SPA) [6] or Full Matrix Capture/Total Focusing Method (FMC/TFM) [7].

**Transmission tomography – direct transmission**

The simplest transmission-tomographic configuration is direct transmission (Fig. 2, left). It is analogous to transmission tomography with a single parallel projection at normal incidence.
Consequently, there is no spatial resolution in the axial direction. In the example, pairs of transducers in a transmission and a receiving array on opposite planes of the object are consecutively activated to capture the transmission signals. This is equivalent to a moving virtual transducer pair.

**Transmission tomography – angular diversity**

Equivalent to the reflection case, the most complete transmission-tomographic configuration for single transducers is shown if Fig. 2, right. A single transducer is transmitting at each cycle of the data capture and all other transducers are independently receiving, either one after the other or all at the same time, but independently. This corresponds to measuring parallel projections under a limited number of different angles. The reconstruction algorithm realizes a backprojection in the time domain [8].

![Figure 2](image_url)

**Figure 2.** Two-sided aperture configurations of a combination of transducers used for transmission tomography: Moving virtual transducer pair (left) and combination of transducer pairs (right)

**3. Reflection-tomographic measuring system**

For reflection tomographic measurements the integrated, automated ultrasonic imaging system FLEXUS was developed. The system is mainly aimed at 3D-imaging of concrete structures in the laboratory and in the field. It consists of a commercial low-frequency ultrasonic instrument, a mechanical scanner, and a software environment for operation, image calculation, and image display (Fig. 3). Depending on the application, single-channel transducers or multi-channel transducer arrays are employed using different coupling methods. At one-sided access, two-dimensional and three-dimensional images of concrete regions can be generated largely automatically.

The ultrasonic instrument was made by Ing.-Büro Dr. Hillger, Braunschweig, Germany. A frequency range from 20 kHz to 10 MHz, a variable rectangular burst sender, and a set of reception filters make it specifically suited for low frequency applications. The mechanical 3-axes scanner has a scan area of 1.00 m × 0.80 m; for larger scans the system is moved manually. The measurement system is operated from control programs for the ultrasonic instrument and the scanner. The imaging software handles all pre-processing of the data and computes two-dimensional and three-dimensional SAFT and C-SAFT reconstructions. Three-
dimensional iso-surface views can be generated and rotated in real-time, and depth correction, target border detection, and stochastic signal detection can be applied.

Directly after completion of the measurements, a three-dimensional volume representation of the inspected region is available that is composed from the two-dimensional cross-sections (sliced 3D SAFT/C-SAFT). A completely focused three-dimensional SAFT reconstruction can be computed as needed.

The electronic FLEXUS scanner was developed in order to accelerate data acquisition and image calculation. The scanner consists of a transducer array and an electronic multiplexer. Fig. 4 shows the FLEXUS transducer array consisting of 48 transducers which are arranged in 16 groups of three transducers each. It uses 55 kHz shear wave transducers made by ACSYS, Moscow, Russia. By means of their ceramic tips, direct (dry) coupling and therefore simple operation with automated scanners is provided. During measurement, every transducer group in the FLEXUS transducer array is dynamically switched between transmission, reception, and deactivation. The user can configure arbitrary control patterns, so all reflection tomographic techniques can be realized.

Fig. 5 depicts two measurement results obtained at a concrete test specimen. The specimen has a size of 1.2 m x 0.8 m x 0.3 m and consists of C30/37 concrete with a maximum aggregate size of 16 mm. It contains three empty tubes, three lens-shaped acoustical voids,
and a few reinforcement bars. Each measurement consists of five tracks. The upper part of Fig. 5 shows the result of a measurement with a moving virtual transducer and SAFT reconstruction. The virtual transducer includes a total of nine transmitting and nine receiving transducers, each comprising three groups of three transducers. The image shows indications of all three tubes and two of the three voids. While the third void is too close to the surface to be imaged, it can be indirectly detected by its shadow on the back wall. Structural speckle noise is barely visible, but the indication borders are a bit uneven and rough. Besides that the image is quite usable for detection and location purposes.

The lower part of Fig. 5 displays the result of a combination-of-transducers measurement and subsequent C-SAFT reconstruction. Benefitting from less structural speckle noise the indications are much smoother, and even the jump in the tube diameter is visible. The indication of the second tube is nicely reassembled from two halves each taken from a different measurement track. As a drawback, the shadow of the third lens on the back wall is lost.

Figure 5. Iso-surface-representation of the 3D-SAFT-C-SAFT-reconstruction made from 2D slices of a specimen, top view: Moving virtual T9/R9-transducer (SAFT, top) and combination of T3/R3-transducers (C-SAFT, bottom)
4. Transmission-tomographic measuring system

The ultrasonic imaging system FLEXUS 120 contains 120 electronically switchable transducers for semi-automated measurements using transmission tomography. The application is the testing of refractory (fire resistant) bricks. The system consists of a low-frequency ultrasonic instrument, a transmitting and a receiving array, and a multi-axial mechanical structure (Fig. 6).

Main items are a transmitting and a receiving array with 60 transducers each covering an area of 180 mm × 100 mm in an 10 × 6 arrangement. Electronic multiplexers are integrated in each of the arrays which can be programmed in any sequence. Thereby all transmission tomographic techniques can be realized with random pairs of transmitting and receiving transducers in 60 to 3600 combinations. The transducers are low-frequency dry point contact (DPC) transducers made by ACSYS, Moscow, Russia. All electronics including the ultrasonic instruments and the multiplexers are made by Ing.-Büro Dr. Hillger, Braunschweig, Germany; the arrays were developed and assembled at MFPA Weimar.

Results of transmission-tomographic measurements are displayed in Figs. 8 and 9. The measurements were carried out at an MgO-C refractory brick with dimensions of 230 mm × 115 mm × 100 mm. The setup prior to pressing the transducers to the brick is shown in Fig. 7.
Fig. 8 depicts the time-of-flight measurement result in direct transmission. Larger transit times typical for inhomogeneities in the material are shown darker. Both the raster image and its interpolated version indicate large conspicuous regions especially in the outer parts of the brick.

![Figure 8. Direct transmission of the refractory brick from 60 single measurements: C-scan in the 10 x 6 measurement grid (left), interpolated C-scan (right)](image)

A transmission-tomographic measurement with angular diversity shall reveal if the indications are depth dependent. Fig. 9 displays the time-of-flight reconstruction result which was calculated from 1768 single measurements, each belonging to a different transmitter/receiver combination. The maximum displacement between transmitter and receiver was four grid points. The surface of the image defines the border to larger transit times in the red volume. In this case the transmission-tomographic result suggest that the conspicuous regions are equally distributed over the depth except for the bottom area.

![Figure 9. Diffraction tomography of the refractory brick from 1768 measurements (iso-surface-representation)](image)

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References