Reverse Time Migration: Introduction of a New Imaging Technique for Ultrasonic Measurements in Civil Engineering

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Abstract

Ultrasonic echo testing is widely used in non-destructive testing in civil engineering to investigate concrete structures, to measure thickness as well as to locate and characterize built-in components or inhomogeneities. Currently SAFT algorithms (Synthetic Aperture Focusing Technique) are mostly used for imaging. These algorithms are highly developed but have some limitations. For example it is not possible to image the lower boundary of built-in components like tendon ducts or vertical reflectors.

We transferred a geophysical migration technique, the Reverse Time Migration (RTM), to non-destructive testing in civil engineering to improve the imaging of complicated structures in concrete. By using the information from wide angle reflections as well as from waves reflected more than once there are fewer limitations compared to SAFT. As a drawback the required computing power is significantly higher as for the techniques currently used.

First simulations for polyamide and concrete showed the potential for non-destructive testing. The simulations were followed by experiments at a polyamide specimen. Here, having acquired almost noise free measurement data to test the algorithm, we were able to determine shape and size of boreholes with a sufficient accuracy. After these successful tests we performed experiments at concrete members in the laboratory as well as at a reinforced foundation slab and at a bridge girder. We obtained information from the data by RTM (e. g. shape of tendon ducts), which was not accessible by traditional imaging. The imaging of the location and structure of the lower boundary of the concrete foundation slab could be improved. Furthermore vertical reflectors inside the slab could be imaged clearly and more flaws could be found. It has been shown that RTM is a step forward for ultrasonic testing in civil engineering.

Keywords

ultrasound, imaging, reverse time migration, reflection seismics, concrete

1. Introduction

Ultrasonic echo and transmission techniques are used in civil engineering on a regular basis. New sensors and data processing techniques have led to many new applications in quality assurance, structural investigation as well as health monitoring. The state of the art is described e.g. in [1], [2], [3]. Main targets in ultrasonic concrete inspection are thickness measurements, geometry determination, localization and characterization of tendon ducts as well as detection of quality issues (honeycombing, cracks, low concrete strength).

More than 10 years ago, the application of ultrasonic echo methods to concrete inspection was limited, as only quite large, heavy transducers were available, which also required a coupling agent. Meanwhile lightweight point contact transducers for compressional and shear waves (25 - 150 kHz) have been developed, which can be coupled to a surface by light pressure without agents.

Data processing and imaging is currently mainly done by Synthetic Aperture Focusing Techniques (SAFT). In fact, the term SAFT is used for an entire family of imaging techniques in time and frequency domain. Some of them are closely related to seismic imaging techniques as Kirchhoff or Stolt migration. Recently, improvements of SAFT, namely phase evaluation to characterize reflectors, have been published [4]. However, the capability to image vertical, deep, or hidden reflectors is limited. For example the determination of the cross section of tendon ducts has not been possible until now. For this reason advanced geophysical imaging techniques as one way wave equation imaging were tested for their applicability [5]. In this paper we have focused on Reverse Time Migration (RTM) due to its known capability to image steep reflectors and to use more information than just direct reflections. Within the next sections we will introduce the imaging methods used and demonstrate the application of RTM to experimental ultrasonic echo data, which were collected on a polyamide and concrete specimen.

2. Imaging Methods

2.1 Synthetic Aperture Focusing Technique

The Synthetic Aperture Focusing Technique (SAFT) algorithm we used in this work operates in the time domain and is a diffraction stack, similar to the Kirchhoff depth migration method from geophysics. Ultrasonic data is measured on the surface of the test object along a line or a 2D area by using, in most applications, a zero offset geometry. This means that the receiving and transmitting transducer have a fixed distance of only a few centimetres.
For the processing of the received ultrasonic signals the SAFT algorithm divides the subsurface into small image elements. For each element the two way travel time for a specific source-receiver configuration is calculated. The corresponding received signal at the calculated time is assigned to it in terms of amplitude and phase. For the final image the SAFT algorithm superimposes the results of all configurations, thus synthesizing an ultrasonic transducer of the size of the total aperture with the ability of variable focusing to each image element [6].

2.2 Reverse Time Migration

The RTM method is a wavefield-continuation method in time and uses the full wave equation. It was introduced by Mc Mechan [7] and Baysal et al. [8] and is now a standard imaging technique in seismic industry. Two of the authors of this paper proved the applicability of RTM in non-destructive testing (NDT) to image synthetic ultrasonic data generated with polyamide and concrete-like models [9]. Beniwal and Ganguli [10] recently published an example for the usage of RTM on focused synthetic and experimental ultrasonic data.
In contrast to SAFT, RTM uses the entire wavefield including multiple reflections. Thus, it is capable of handling multi-pathing and many other complex situations. Steeply dipping reflectors and reflectors in areas with strong velocity variations can be imaged by using RTM. A major disadvantage of this technique is the extensive computing power and memory capacity required.
We tested two different RTM implementations in this paper. Both algorithms use a numerical solution of the 2D acoustic wave equation. In our measurements we used horizontally polarized shear waves which, in the 2D case, do not convert to other types of waves at interfaces. Thus, using a 2D acoustic RTM code is kinematically correct.
For RTM, two independent finite difference simulations are performed by using an estimated velocity/density model of the investigated medium followed by the application of an imaging

condition. The same numerical velocity/density model is used for both simulations. Figure 1 illustrates the principle of RTM. For demonstration, we chose a two dimensional model which contains a concrete structure embedded in sand soil. Steps two to four are performed separately for each source-receiver configuration.

1.) Estimation of a velocity/density model.
2.) The source wavefield W_S is extrapolated forward in time using the source location, the source wavelet and the estimated velocity/density model.
3.) The receiver wavefield W_R is propagated backward in time, from all receiver locations using the recorded data as well as the same velocity/density model.
4.) The imaging condition used in this work (1) computes the zero lag local cross-correlation between the two simulated wavefields W_S and W_R at all model grid points to find the positions of subsurface reflectors (cf. [11]):

$$\mathrm{I(x,z)} = \int_0^T W_S\,(x,z,t)\; W_R(x,z,t)dt \tag{1}$$

where I(x, z) is the image at location (x, z) and T is the recording time.
5.) For the final result, the correlation images of all configurations are stacked.

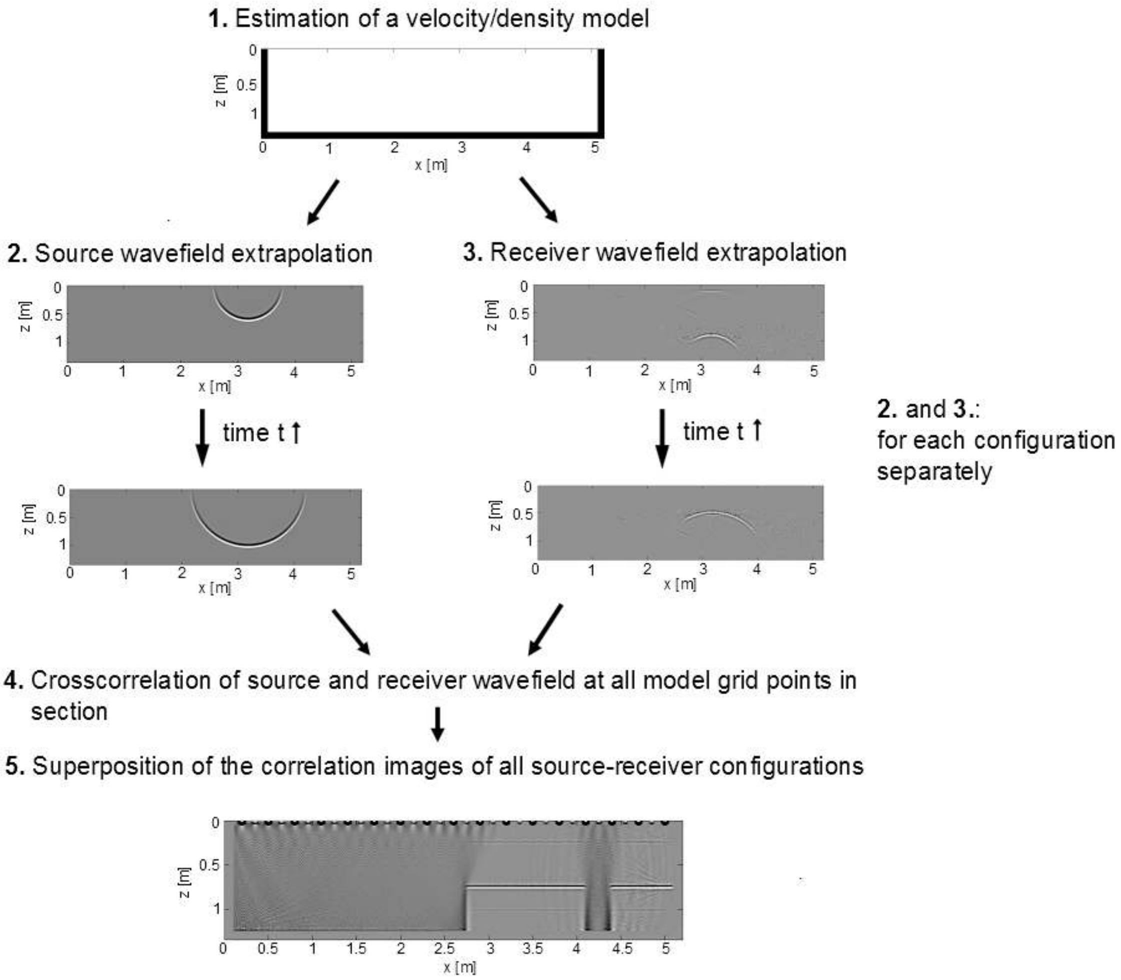

Figure 1. Principle of Reverse Time Migration

3. Measurement Equipment

For the ultrasonic measurements at polyamide and concrete we used a multistatic arrangement. In that case two ultrasonic transducers which are separated from each other are moved over the surface and change their positions and distances. Furthermore a scanner system was used for speed and accuracy (Figure 2). The system used is half-automatic, so the source had to be moved manually but the receiver was moved by the scanner.
Furthermore, different transducers were used for the measurements. The specifications of these transducers and details about the measurement setup are given later. To collect the data at polyamide and concrete the same laboratory measurement equipment (Laptop, DAQ-Pad, signal generator and amplifier) was used.

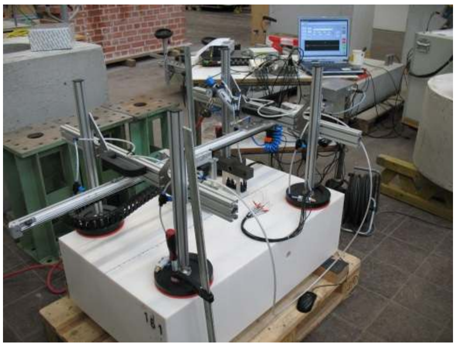

Figure 2. Half-automatic scanner for the ultrasonic measurements at polyamide and concrete

4. Evaluation on a Polyamide Specimen

First measurements were done at a polyamide specimen to show the potential of RTM for non-destructive testing and to find out if we can achieve quantifiable results. The measured data is relatively noise-free because polyamide is a homogeneous material without aggregates. The specimen is shown in Figure 3. It has a size of 1 m x 0.6 m x 0.3 m. In a series of experiments a borehole was drilled parallel to the surface. Its diameter was enlarged stepwise from 2 cm to 5 cm. Below we present data acquired over a drilled hole with 5 cm diameter.

Figure 3. Polyamide specimen with hole drilled parallel to the surface

The acquisition geometry comprised 12 source positions with a distance of 8 cm and 45 receiver positions with a distance of 2 cm at one single profile at the polyamide specimen perpendicular to the axis of the hole. We used transducers consisting of 4 point contact transducers which are connected in parallel. For these transducers no couplant is needed. With

the interconnection of 4 transducers the quality of the data is improved.
The transducers can be switched between longitudinal wave mode and shear wave mode. We used shear waves polarized perpendicular to the measurement direction. We used a ricker wavelet with a center frequency of 50 kHz and recorded data for 0.0012 s with a time step of $1 * 10^{-7}$ s.
The data was then processed by a high-pass filter (f=15 kHz) and automatic gain control (AGC) to improve the quality and reduce influences by surface waves. Data were interpolated to a time step suitable for numerical simulation. A 3D/2D-correction was used to analyze 3D-data with the 2D-RTM [12]. All these processing steps were done with MATLAB.
The main parts of the used program code, especially the modeling part, have been written by Thomas Bohlen (KIT, Germany) [13]. First add-ons for RTM were developed by Maria Baumann-Wilke [14]. André Kurzmann did a lot of improvements in the context of his PhD thesis [15]. Although the code is limited to the 2D acoustic case, it is possible to analyze shear wave data due to the directivity pattern of the transducers.
For the RTM a velocity model is needed. We used a homogeneous rectangle surrounded by an layer of air. The size (1 m x 0.3 m) and the shear wave velocity (1150 m/s) of the specimen can be measured and is assumed as known. No information about the drilled hole is provided in the model. At the model boundaries we used perfectly matched layers with 5 % amplitude decay at outer edge. Figure 4 shows the result of RTM. We can detect clearly the drilled hole as a circle. The measured diameter from the migration result is 5.2 cm and so only 4 % higher than the real value. The entire perimeter of the specimen is detectable. Some artifacts at the top of the specimen are visible. They are a result of the cross correlation at the positions of the sources and the receivers.

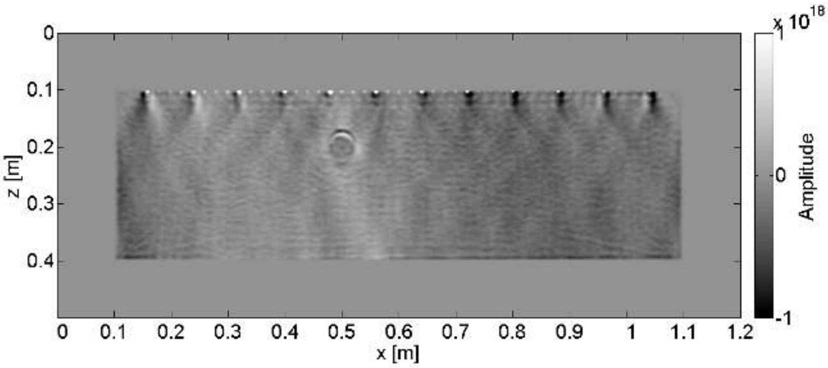

Figure 4. Result of RTM of the measurement at a polyamide specimen with a drilled hole

5. Test on a Concrete Specimen

For a second test, this time on concrete, we chose a reinforced concrete foundation slab (Figure 5). The foundation slab is embedded in compacted sand and consists of areas of different thickness (1.25m and 0.75 m), various different reinforcement levels, two piles and a strip foundation. A layer of lean concrete with a thickness of 0.05m is located below the bottom of the foundation slab. Figure 5b shows the lean concrete layer and the different levels of reinforcement before placing concrete. The tasks with respect to the foundation slab were thickness determination as well as imaging the vertical step and the two pile heads.
The ultrasonic data were recorded along a line profile on the foundation slab (Figure 5a) which crosses the vertical step, a pile and the reinforcement meshes A1and B1. The ultrasonic transducer we used in this example consist each of 32 dry point piezoelectric contact

transducers connected in parallel which excite shear waves polarized perpendicular to the profile direction.

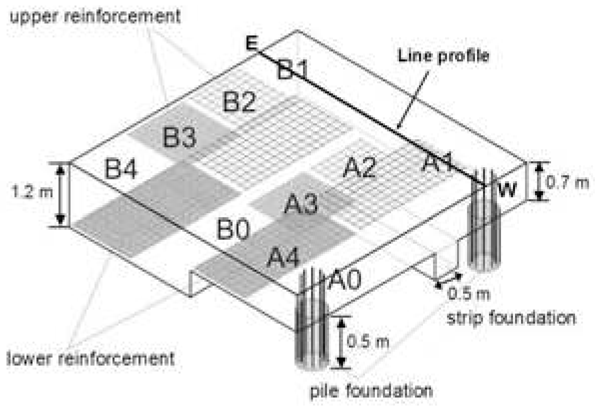

Figure 5. a) Geometry of RuFUS foundation slab and b) lean concrete layer and different levels of reinforcement before placing concrete (cf. [16])

The parameters for the ultrasonic measurements are listed in Table 1. Source-receiver offsets were limited to a maximum of 2.3 m due to the range of the scanner. The first source position was located 0.1 m from the eastern boundary (E, Figure 5a).

Parameter	
Source frequency	25 kHz
Time step	$1 \cdot 10^{-6}$ s
Recording time	0.003 s
Number of sources	32
Number of receivers	varies
Distance between sources	0.15 m
Distance between receivers	0.02 m
Source position no. 1	0.1 m
Receiver position no. 1	0.21 m

Table 1. Measurement parameters

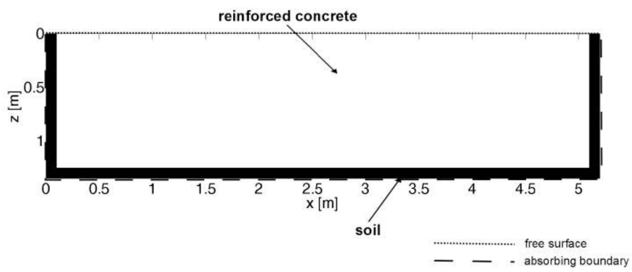

Figure 6. Velocity/density model used for RTM

For RTM of the ultrasonic data collected on the concrete slab we worked with an algorithm based on a 2D finite difference modeling code included in the Madagascar software package [17]. The structure of the velocity/density model which we used for RTM is shown in Figure 6. The boundary conditions used are marked accordingly. The outer limits of the foundation slab are assumed to be known. The other migration and material parameters are summarized in Table 2. We chose a migration shear wave velocity of 2740 m/s for the reinforced concrete layer based on a preliminary velocity analysis. The migration shear wave velocity of the sand soil layer was set to 300 m/s. As source signal a Ricker wavelet with a center frequency of 25 kHz was used.

Parameter	
Model size	5200 x 1350 grid points
Distance between grid poinzs	0.001 m
Frequency Ricker wavelet	25 kHz
Time step	$1 \cdot 10^{-7}$ s
Recording time	0.0017 s
Number of sources	32
Number of receivers	varies
Distance between sources	0.15 m
Distance between receivers	0.02 m
Source position no. 1	0.02 m
Receiver position no. 1	0.031 m
Velocity and density concrete	2740 m/s and 2400 kg/m^3
Velocity and density sand soil	300 m/s and 1800 kg/m^3
Thickness of concrete layer	1.25 m

Table 2. Parameters for RTM

Prior to RTM we performed the following processing steps on the ultrasonic measurement data: muting electronic crosstalk, time interpolation and bandpass filtering (cut-off frequencies: 8 kHz/100 kHz).
Figure 7 shows the resulting RTM image. The lower boundary of the foundation slab is reproduced at the correct depths but showing a low amplitude at the model boundaries.

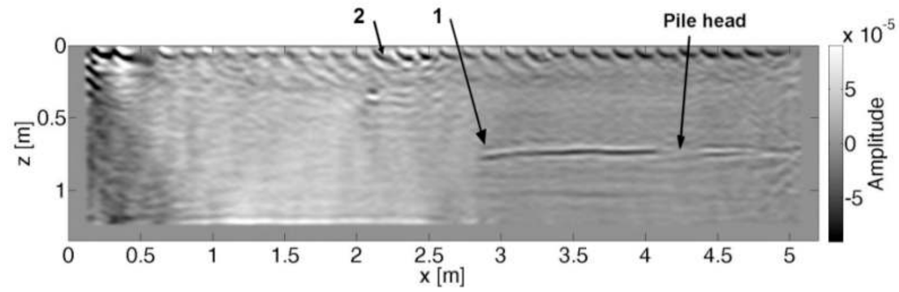

Figure 7. RTM image of the line profile (1: slight dip of the lower boundary of the slab and 2: migration artifacts caused by direct waves)

Furthermore, the structure of this boundary shows some roughness and a slight dip in the area of the vertical step ("1" in Figure 7). The pile head is reconstructed at the correct position. The position of the step is shifted by about 0.1m to the right compared to the construction drawings. The pile shaft and pile base could not be imaged. At x = 2.1 m and z = 0.3 m a circular reector is visible, caused by a metal bracket. The semi-circular artifacts at the source positions ("2" in Figure 7) are caused by direct waves. These arrivals have not been suppressed before the application of the migration scheme.
For the next RTM image (Figure 8) we additionally applied AGC and trace normalization to the ultrasonic data. In addition, we stacked the images of shot points no. 7 to 15 only. The result clearly illustrates that the vertical edge of the step is reproduced at x = 2.85 m.
Figure 9 illustrates the image obtained by performing the homogeneous 3D-SAFT reconstruction using the Intersaft software [18]. For the imaging process the migration velocity was set to 2740 m/s and we used the raw data processed with a band pass filter (cut-off-frequencies: 8 kHz to 100 kHz). Furthermore, we eliminated the direct waves and their

reflections at the lateral boundaries of the slab, as long as a clear separation of other relevant events was possible.

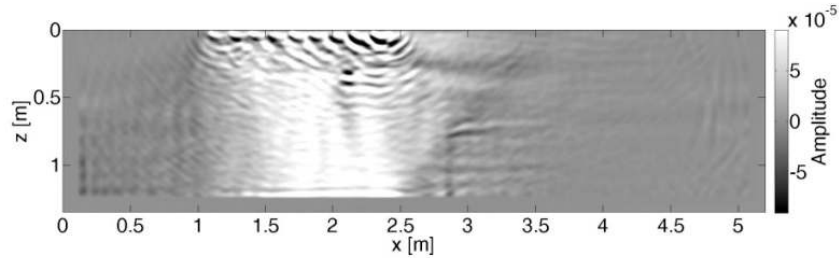

Figure 8. RTM image of line profile after stacking the images of the shot points no. 7 to 15 and applying AGC and trace normalization to the data

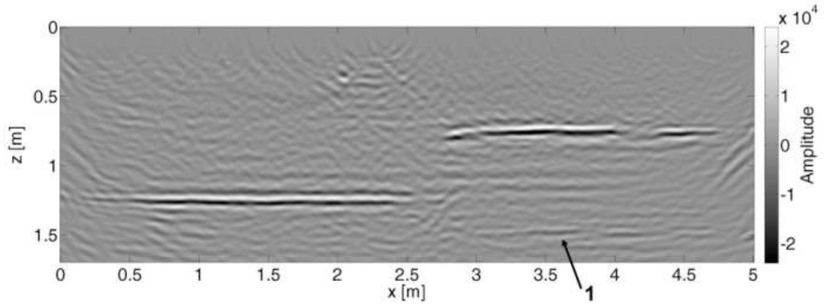

Figure 9. SAFT-reconstruction of line profile after applying a bandpass filter and eliminating the direct waves in the measurement data (1: reflector caused by multiple reflections in the data)

In the image obtained with SAFT the lower boundary of the slab, the pile head and the metal bracket are clearly visible. Similar to the RTM result the horizontal shift of the position of the step, the dip of the lower boundary of the slab in the vicinity of the vertical step as well as the roughness in the structure of the lower boundary were reconstructed. A reflector caused by multiple reflections in the data can be observed at a depth of z = 1.43 m ("1" in Figure 9). The result clearly illustrates the limitations of SAFT since no vertical interfaces were imaged, even with stacking the reconstruction results of shot points no. 7 to 15 only.

The comparison between RTM and SAFT shows a significant improvement in imaging the geometry of the foundation slab by using RTM. No vertical features inside the slab could be reconstructed with SAFT. However, with RTM we have been able to image the vertical boundary of the step and to improve the imaging of the structure of the lower boundary of the slab.
The SAFT algorithm is based on the approximative integral solution of the wave equation and normally only the shortest wave paths between sources and receivers are considered. Thus for a subsurface with strong velocity variations and the associated changes of the wave propagation paths, no optimal migration result can be achieved. In contrast to SAFT, RTM directly solves the wave equation and is thus more accurate. It enables the imaging of reflectors with inclinations > 70°, even in media with strong velocity contrasts, because all wave types and multi-pathing are taken into account.
In all migration images a horizontal displacement of the vertical step of about 0.1 m was reconstructed compared to the construction drawings. As the pile head was imaged at the correct position, the displacement of the step might be an error in the construction plan. The imaging of the pile shaft and the pile base was not successful, because the measured data

show noisy signals emanating from the piles. Reasons are, inter alia, the large amount of reinforcement, edge effects and multiple reflections at the pile shaft.

6. Conclusions and Outlook

The applicability of RTM to image ultrasonic echo data was evaluated based on measured data. Experimental data were recorded in two different setups: a homogenous, isotropic polyamide specimen and a realistic, inhomogeneous reinforced concrete foundation slab. Both tests yielded promising results and showed that RTM is a step forward for the ultrasonic echo technique used in NDT.

With the measurements on a polyamide specimen it was possible to detect a drilled hole in its complete perimeter, i.e. also the bottom of the hole. This puts us in a position to measure the diameter of the hole and to perform a quantitative determination of the interior geometry of the specimen. Here, we achieved an accuracy of the diameter of 4% compared to the real value. This would not be possible with SAFT-algorithms. Furthermore, the imaging of the location and structure of the lower boundary of the investigated concrete slab could be improved with RTM compared to SAFT. By using RTM a vertical border was imaged clearly and more flaws were found.

RTM artifacts have to be analyzed and eliminated. For this task alternatives to the cross-correlation imaging condition as well as pre-imaging filtering techniques may be used. In addition, the algorithm should be expanded to three dimensions and the full elastic wave equation. The use of adopted source signals should improve the image quality as well. Another topic to be addressed is to how to account for the size of the ultrasonic arrays. The RTM codes used in this work assume point sources. Hence, the migration algorithm does not calculate the shot and receiver wavefields fully correctly.

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