Improvements on Tendon Duct Examination by Modelling and Imaging with Synthetic Aperture and One-Way Inverse Methods

Gregor BALLIER 1, Klaus MAYER 1, Karl-Jörg LANGENBERG 1, Sebastian SCHULZE 2, Martin KRAUSE 2

1 University of Kassel, Kassel, Germany; Phone: +49 561 804 6488; gregorballier@uni-kassel.de, kmayer@uni-kassel.de, langenberg@uni-kassel.de
2 German Federal Institute for Materials Research and Testing, Berlin, Germany; Phone: +49 30 8104 4269; Sebastian.schulze@bam.de, martin.krause@bam.de

Abstract
The knowledge of the internal structure of tendon ducts is one of the important preconditions to make predictions about the stableness and the lifetime of concrete buildings – specifically concrete bridges. Ultrasonic NDT methods can be used to have a look inside those components. To understand the complex effects resulting from elastic wave propagation, it is important to build test specimens and to analyze the measurements with the aid of modelling. At BAM (German Federal Institute for Materials Research and Testing) a new specimen is under construction to realize some of the most common geometrical structures which can be expected in the field of tendon duct testing in concrete bridges. We present various measurement concepts and a comparison between measurement and modelling with EFIT (Elastic Finite Integration Technique), as well as results of imaging methods based on conventional SAFT (Synthetic Aperture Focusing Technique) or FT-SAFT (SAFT with Fourier Techniques) together with phase evaluation. In addition we will present the results of time reversal using AFIT (Acoustic Finite Integration Technique) and a one-way wave propagation method to improve the imaging.

Keywords: Ultrasonic NDT, concrete, SAFT, one-way, AFIT, time-reversal

1. Introduction

During the last years NDT with ultrasound has been very successful in imaging the inner structure of objects with the help of impulse-echo-measurements and the SAFT-method. The problems with this method which arise for many objects to be investigated, e. g. components of bridges (Fig. 1), are the inhomogeneities of the objects itself. Concerning tendon ducts: due to the assumption of a homogeneous medium used for data propagation, the conventional SAFT-method only allows to reconstruct the upper boundary of the duct correctly. The lower edge and grouting faults cannot be imaged at their correct position because of the wrong velocity assumption.

This disadvantage of SAFT can be overcome by means of numerical methods like AFIT (Acoustic Finite Integration Technique) or a one-way wave propagation technique. Both methods allow to consider the inhomogeneities during back propagation of measured data. Thereby we obtain an improvement in the reconstruction of the inner structure of the object.

With respect to the generation of data and the usage of the algorithms to be applied, we restrict us to the impulse-echo-method (see Fig. 1b). The transducer sends pulses from different positions on the surface and receives the scattered signals at the same positions.
2. Basics

In this section a short overview on the applied methods will be given. For a detailed explanation of the algorithms please refer to the references.

2.1 SAFT

SAFT (Synthetic Aperture Focusing Technique) is a heuristic imaging algorithm [1] applicable for scalar waves and is used successfully for ultrasound applications. It can be applied directly to the measured time data to obtain a reconstruction. The principle of the algorithm is as follows: Assuming a homogeneous background medium, the time axis is converted into a distance axis according to the half of the background velocity and a single A-scan is transformed into a semicircle in space with the origin at the sending/receiving position. The superposition of all processed A-scans provides the reconstruction of the scatterer (see Fig. 1.c).

2.2 AFIT and One-Way

AFIT and the one-way method are based on the basic equations of the acoustic theory [10] and primarily serve as modelling tool. They describe the wave propagation in gas, liquids and under specific conditions in solids, too [1]. To describe wave propagation in solids exactly we need to consider the governing equations for elastic waves. As a result, in solids we have pressure (P), shear (S), and surface waves and waves change from P to S (mode converted waves) and vice versa if the wave field interacts with an inhomogeneity. So, the description of waves in solids applying the scalar acoustic theory leads to neglecting the P or S, and the mode converted waves.

2.2.1 FIT

Historically, the finite integration technique (FIT) was first applied to the set of Maxwell’s equations in integral form [2] for electromagnetic wave propagation. In [3] we find the first realization for elastic waves and in [4] a detailed elaboration and derivation for the acoustic, electromagnetic, elastic and the piezo-electromagnetic case. FIT is used for the direct
discretization of the governing equation of the acoustics. The linearized acoustic equations in integral form are

\[
\int \int \int \int \int \int \int \rho(R) \partial_t v(R,t) dV = - \int \int \int n p(R,t) dS + \int \int \int f(R,t) dV \tag{1}
\]

\[
\int \int \int \kappa(R) \partial_t p(R,t) dV = - \int \int n \cdot v(R,t) dS - \int \int h(R,t) dV \tag{2}
\]

with \(p(R,t)\), the acoustic pressure [Pa], \(v(R,t)\), the particle velocity [m/s], \(\rho(R)\), the volume mass density [kg/m\(^3\)], \(\kappa(R)\), the adiabatic compressibility [Pa\(^{-1}\)], \(f(R,t)\), the volume force density [N/m\(^3\)], and \(h(R,t)\), the injected deformation rate [s\(^{-1}\)].

2.2.2 The One-Way Method

The 'one-way method' (the directional wave-field decomposition) originates from problems of atmospheric wave propagation [5]. The method is used in integrated optics, underwater acoustics and especially in seismic exploration. It is a useful tool for wave field analysis and computation, because it is computationally very efficient and can be used to separate different propagation phenomena. This can be very important for the interpretation and inversion of measured data [5]. The numerical implementation is based on equation (1) and (2) in differential form. We apply a rational approximation approach – finding the roots in the parabolic equation method [7, 6] – with ansatz we get a partial differential equation that we transform into a system of ordinary differential equations. At the end we have an algebraic system – containing a sparse matrix – that we can solve efficiently.

Both methods handle correctly the forward multiple scattering problem including focusing, defocusing, diffraction, refraction and interference of waves. The difference between the methods is that the one-way method neglects the wave reverberations between heterogeneities [9].

2.3 Comparison of AFIT to the One-Way Method

For the comparison of AFIT to the one-way method we use a reference medium as displayed in Fig. 2a. It is based on a concrete component that can be found in bridges. The component mainly consists of concrete with five rebar steels imbedded and one tendon duct filled with mortar. On the surface we excite a source point with an RC2 pulse (raised cosine with two cycles). In Fig. 2b the AFIT wave field snapshot is shown at time \(t_0\). We clearly see how the wave field is deformed by the heterogeneities. Furthermore, we see the reflection of the lower and upper edge of the duct, the mirroring reflection on the surface of the middle rebar steel and also multiple reflections. The reflected waves from the scatterer travel again into the object because of the boundary condition on the surface. In Fig. 2c we see the one-way wave field at time \(t_0\). The method only shows the forward travelling wave field and no reflections.
The advantage of the one-way method compared to AFIT is that we get no reflections from heterogeneities which can lead to problems when interpreting back propagation results.

3. Results

In this section we present the comparison of image reconstructions obtained by SAFT, AFIT and the one-way wave technique. These techniques are applied to synthetic and measurement data of an impulse-echo experiment. First we analyze one trace of the measurement at the specimen shown in Fig. 3, considering the location and the structure of the duct. A detailed report of this specimen can be found in [10, 11]. To use AFIT and the one-way method as a reconstruction tool, we have to process the data in a reversed time arrangement and we call these applications 'AFIT inverse' or 'one-way inverse', respectively.

Figure 2. a) Reference medium to compare AFIT to one-way. On position x we excite a source point with an RC2 impulse. $c_{ste} = 5900$ m/s, $c_{mor} = 3600$ m/s and $c_{con} = 4326$ m/s. Comparison of the wave fronts of AFIT b) and of the one-way method c).

Figure 3. a) Test specimen from BAM (FBS1), overall dimension $x = 1.5$ m, $y = 2.0$ m and $z = 0.5$ m. b) B-Scan of measuring trace. c) Tendon duct between $z = 0.27$ m and 0.35 m with tendons and air inclusion. d) Geometry for the back propagation of the measurement.
3.1 Measurement

In Fig. 4 we see the reconstruction of the specimen in Fig. 3, with SAFT, AFIT- and one-way inverse. In the case of 'AFIT inverse' and 'one-way inverse' for back propagation of the data we use the model in Fig. 3d. In each case we see the upper boundary of the duct clearly. In the case of SAFT we see that the location of the lower boundary is deeper than expected because of the assumed homogeneous medium that we use for back propagation. In the other two cases we see an improvement in the images for the lower boundary, compared to SAFT.

Figure 4. Reconstructions of data from test specimen in Fig. 3 with SAFT (first row), AFIT (second row) and one-way (last row). Left: real part, right: magnitude of the image.


3.2 Synthetic data

In the next step we model two setups with synthetic data obtained by EFIT (Elastic Finite Integration Technique). We want to compare tendon ducts with and without air inclusions (voids). In Fig. 5 we see the geometry for generating the synthetic data, a B-Scan, the geometry for the back propagation of the data, and the frequency spectrum for these cases, respectively. We made the assumption that there are no defects in the model for back propagation of the data. The purpose of AFIT and one-way technique is to improve the image of the back wall of the tendon duct and the location of defects.

Again: in every case we have a good image of the upper edge of the duct. Multiple reflections lead to interference in the case of 'AFIT inverse' so that we get a poor image of the back wall of the tendon duct and the air inclusion. In the case without air inclusion (right side of Fig. 5), the SAFT algorithm images the lower edge deeper and 'one-way inverse' shows only a weak image. In the case with air inclusion we have a clear image of the defect with 'one-way inverse'. However, the location of the defect is a little bit deeper.

Figure 5. Geometry of the setups for modelling (A), geometry for the back propagation (B), B-Scans (C) and the spectra (D) from the synthetic data produced by EFIT. Left we see the case with an air inclusion and on the right without.
4. Conclusions

As we have seen: for measurement and for synthetic data SAFT provides a correct image of the upper edge of the tendon duct. The lower edge (the back wall) will be depicted at the wrong location because the conventional SAFT does not account for inhomogeneous media. In the case of the evaluation of the measurement we have a clear image of the lower edge both with 'AFIT inverse' and 'one-way inverse'. Certainly the image of the lower edge is wider than expected, we ascribe this on a wave that runs around the duct, a so-called creeping wave.

The comparison of the processed synthetic data shows: 'AFIT inverse', with and without air inclusion, provides a bad result, neither the lower edge nor the air inclusion is recognizable. Multiple reflections lead to destructive interference. The evaluation with 'one-way inverse' clearly shows the lower edge and the air inclusion.

As a conclusion: In a first step with SAFT we get a fast indication of the upper edge of a duct. But for better depiction of the lower edge or a defect we have to use 'one-way inverse' or 'AFIT inverse'. The result of the measurement shows that 'AFIT inverse' can provide good, but in all three cases the 'one-way inverse' method provides the best results.

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Figure 6. Reconstructions of the geometry of Fig. 5 with SAFT (first row), AFIT (second row) and one-way (last row). Displayed as real part and magnitude of the image. Left with an air inclusion and on the right without.
References