



# Requirements for a Small Size Ultrasonic Imaging System for Inspection of Concrete Elements

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**Abstract.** Ultrasonic imaging systems usually require an array of ultrasonic transducers for data acquisition on a wide area on top of an object under investigation. The goal of an imaging algorithm is the use of reflected ultrasound data to form a recognizable image. Conventional algorithms like SAFT are based on an inverse Huygens' principle and need therefore a dense measurement grid. This requires a big effort in data capturing. For simple and inexpensive measurement different strategies of imaging with reduced amount of data and examples with a manual scanning device on concrete elements are presented.

## Introduction

The following article describes intermediate results of a research project to ensure the quality of new and existing buildings made of concrete by innovative non-destructive testing. The aim of the research project is the specialization of imaging techniques for manual data recording.

Thus, it should be achieved to quickly prove the interconnection of components in the context of quality assurance in the construction. These may be precast or prestressed concrete components. In contrast to the automatic measurement, the positions of the probes should be captured and passed to the application software in an arbitrary measurement grid. For the on-site evaluation of non-scanning measurement by the use of synthetic aperture focusing techniques (SAFT) these techniques have to be extended by new concepts [1]. Typical questions for non-destructive testing of quality assurance of construction, repair and conversion of concrete structures are: determination of the construction plan and the design of historical buildings, compression defects in heavily reinforced floors and pillars, grouting defects, honeycombing or statements about the inner state of element walls. It should be emphasized, that only with the new possibilities of the use of ultrasound in the examination of concrete elements these problems could be addressed at all. But from the use of ultrasonic testing in steel it is also known, that an assessment of manual measurements is difficult and sometimes impossible for unknown or complex environments. Nevertheless the potential of ultrasonic methods is proven for many examples, even if these methods are not yet so well established in the practical application.



The reason is, that there is usually a high effort to collect data on a regular measurement grid for synthetic aperture imaging methods [2].

## Experimental Setup

The system for capturing ultrasonic A-scans together with the exact location on the measuring surface consists of three main elements:

- A dual element probe for capturing ultrasonic echo data in a frequency range adapted for concrete (centre frequency around 50 kHz for shear waves and 100 kHz for pressure waves)
- An interface for producing an excitation pulse adapted for the transmitter and a receiving unit for the backscatter pulse with suitable amplification, working with external trigger
- A distance measuring device with pull out measuring filament for measuring the distance between the origin and transducer and additionally the angle between a selectable axis and the current connecting axis of every measuring point. Using the values read by two angle decoders (one positioned in the centre of the body housing and one on the probe housing) the location of the probe is measured in polar coordinates as well as the orientation of the probe housing. The body housing is fixed on the surface by the vacuum produced with help of a small air pump.

This principle is realized by using a commercially available ultrasonic echo system additionally equipped with an external trigger unit [3]. It may principally work with other systems realizing dry coupling of ultrasonic wave pulses in an adequate frequency range [4]. The elements are depicted in Figure 1. The measured signals of values of the filament length and the angle decoder are transmitted to a notebook computer, which is governing the measuring process.



Figure 1: Parts of the manual data capturing equipment (electronic and computer not shown)

For practical application the coordinate system has to be initialized on the measuring surface. This is done by several measuring points along a line indicated on the screen relative to the body housing. Then a new reference point is chosen on the measuring surface and all measuring points will be indicated relatively to this coordinate system.

The measuring process is simply started by selecting user defined locations of the probe and pressing the start button at the grip of the probe. The coordinates are transmitted and calculated together with the ultrasonic A-scan. With the beginning of the first measuring points the evaluation process starts and the current SAFT reconstruction is depicted on the screen as described in § 3 (application example). This procedure is continued little by little and an ultrasonic scan of the investigated building element will get visible. This may be continued until a convincing result is obtained.

## **Data processing methods and software**

### *2.1 General demands*

Following the goal to build a system for handheld application it is important to get an intermediate result at any step of the measurement so that the operator can decide which measurement point has to be selected in the next step. This can only be achieved if the measured signal (A-scan) is analyzed itself by one dimensional methods, because the data for multidimensional analysis are not yet available. The goal of the 1D signal analysis can be to find reflections from known or unknown objects or typical body reflections of the object under concern. The information is categorized into two classes:

- a) Signals which are expected and have to be verified. These are reflections from the back wall or multiples of this and reflections of surface waves at boundaries of the object under test. These signals can help to perform velocity estimation but it is difficult to distinguish different reflection types in 1D signals.
- b) The second category (class b) are the signals from defects or reflectors which have to be investigated like tendon ducts, delaminations, segregations and others.

Criteria have to be developed to distinguish these cases, so that a separation of mixed signals can be achieved. To increase the confidence level of the result a positioning of the source of a reflection is necessary. This can only be achieved by a kind of triangulation. The advanced technique to get this for all kind of reflections is a multidimensional imaging technique like SAFT (Synthetic Aperture Focusing Technique) which is a NDT method derived by the ideas of a wave field inversion or a wave field back propagation [5]. Conventionally SAFT is used for an equidistant measurement grid and usually for a planar surface, which is in general not necessary. The SAFT algorithm, based on diffraction tomography with linear approximation of the scattering mechanism, is calculated in a delay and sum manner which means that for any point in the reconstruction space (the 3D voxel matrix containing the reflectivity properties of the region of interest) a superposition of all sample values corresponding to the time delay a wave would use to travel between transmitter, scattering point and receiver is performed.

### *2.2 1D signal analysis methods*

The background of detecting and characterizing 1D signals is huge, because many applications in the ultrasonic (ultrasound), elastodynamic (ultrasound and seismic) and electromagnetic (radar) try to handle these problems. For our purpose we focus on prominent methods which can be used on small and flexible equipments. The implementation and testing of the methods are still in process, therefore a final evaluation and testing on real objects is not yet available. The selected methods are:

- a) Predictive deconvolution for finding and suppressing multiple reflections [6]

- b) Adaptive deconvolution to overcome some problems of method a) [7]
- c) Sparse deconvolution for pulse compression and classification [8]
- d) Empirical Mode Decomposition for signal segmentation and classification [9]
- e) Model-based echo decomposition for impulse characterization [10,11]
- f) The Tau-p transform in connection with b) for suppression of multiple reflections if the signal repetition rate is not constant [12]

Figure 2 gives an example of the decomposition of a signal gained from the measurement in §3

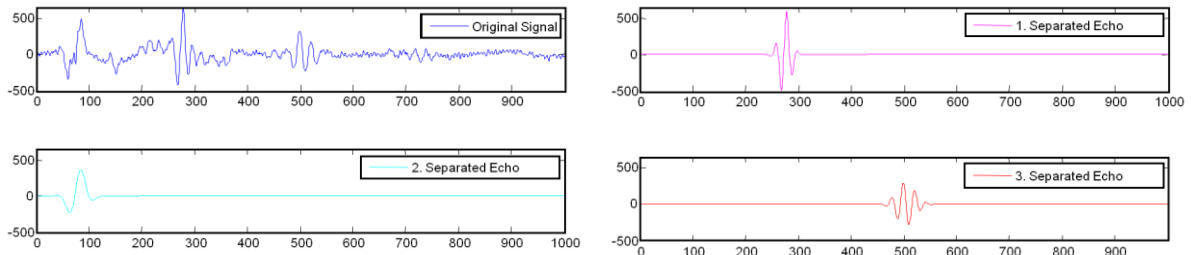


Figure 2: Decomposition of an A-scan by method e) with parameter extraction (not displayed)

### 2.3 2D and 3D imaging method for non-equidistant measurement grid

Using SAFT algorithms with few data is not a good idea at all. This statement is correct, but under the given circumstances SAFT gives us some good hints about position and properties of reflectors, which we should use to understand the result of such measurements. SAFT is the ideal algorithm for processing data coming from small transducers with large beam opening angle [13]. For concrete testing the actual design especially for shear wave generation are dry point contact transducers used as an ensemble of receivers and transmitters in a dual probe transducer unit [3, 4]. The arrangement of 4x3 receivers and 4x3 transmitters in a distance of 2cm delivers a sufficient contact area for examining concrete objects up to 1 m thickness. This specification depends on the aggregate size and the concrete quality and may vary dramatically. Nevertheless the beam opening angle of that transducer is wide enough to get information from all directions. This advantage for SAFT processing is the disadvantage for a pure 1D signal analysis, and therefore both techniques have to be combined for our task. To achieve this an interactive imaging software has been developed which should allow the user to position and to classify reflection indications and give him the possibility to improve the result by successively increasing the number of measurement points. The operation is divided into subtasks:

- Get the next measured data from the measurement facility (one or more A-Scans)
- Do some preprocessing (filtering, DC-extraction) on the A-scans.
- Indicate the positions of the collected data in the aperture plot.
- Use the position of the data to get measurement density information.
- Process the available data to get a B-image and a C-image as a 3D SAFT result using the density information.
- Select your area of interest given by some preliminary information about the examination task.

An arrangement of point reflectors is virtually placed in the area of interest and synthetic data are generated for that arrangement using the same measurement positions and frequency range as the measured data.

SAFT reconstructions are performed at the same place as for measured data with the same reconstruction parameters, so that the user can see whether the selected measurement points are already OK to fulfill the examination task or whether the density of recording points have to be increased.

### *2.3.1 Implementation of the SAFT algorithm*

SAFT is an imaging algorithm based on the backpropagation of the wave field by assuming that the excited wave travels to the scattering object and from there back with the same velocity and the same path (in mono-static case) or via a direct path to a separate receiver (bi-static case). Multiple reflections and different velocities on the way of the wave are not considered because of the physical optics- or Born approximation, which have to be used to get a closed mathematical expression for the algorithm [5]. The summation performed in SAFT is the discrete counterpart of the integration along a continuous wave field reaching the surface. Doing the discretization we have to consider the infinitesimal integration area as a multiplication with the area around a measurement point. On the other side we have to account for the sampling theorem, which gives us a measure for the maximum distance between points in respect to the wavelength corresponding to the frequency content of the signal [14].

If this rate is not fulfilled we expect degradation and therefore problems to understand the result. There are techniques to interpolate data from a non-uniform grid to a uniform grid but these techniques are difficult to understand and difficult to implement for an interactive processing. Fortunately our goal is not to reconstruct the wave field at the surface, but the reflecting objects within a body with known background parameters. The reconstructed object appears by integrating the wave amplitudes coming from all directions of reception. Therefore it is important that the integration gives a sharp peak where a reflection occurs and gives only small values where destructive interference appears. There are many approaches in the field of geophysical or seismic data processing to overcome the problem of acquisition aperture effects [15], but to account for the manual inspection a simple and intuitive approach has to be implemented.

Therefore, we propose a pure amplitude weighting to account for the different spatial distances of measurement points and calculate a synthetic dataset with a test geometry containing some point scatterers which gives the user the possibility to check the resolution capabilities of the data already manually captured. This synthetic data set can be adjusted to contain the same frequency range and a similar beam spreading as the used ultrasonic equipment. The weighting of the A-Scans is determined by superposition of a distant dependent Gauss-function for all acquired positions with the heuristic idea, that many measurement positions in one area give us more energy from the direction which can be assigned to that area, than the contribution from other areas which are covered by less measurement positions. The advantage of this approach is, that the presence of many measurements in an area helps to increase the accuracy because of increasing the sampling rate but also because of reducing the effects of structural noise especially for testing concrete. But the density of the measurement does not affect the amplitude of the reconstruction itself, because the weighting replaces the multiplication of the discrete area size in the integration formula.

This gives us a further advantage against a multiplication of the area size: If we consider for example 2 measurement points, then these two points have to share the whole area of the aperture. If we put a third point to the ensemble, the 3 points will have to share the aperture, while 2 points near to each other share a smaller area, but how should we select the area for each of the three points. In our approach we assume a smooth radius around each point, which depends somehow from the frequency range of the transducer, so

that a point which is not in a neighborhood of other points is not weighted by the whole area around as it would be demanded by the integration formula. To overcome the problem of high density in an aperture region we propose a method which is used in signal processing known as Wiener deconvolution. This means we add a small correction term in the denominator of the weighting correction formula, with the result that high values of the superimposed distance functions for narrow points are less important than lower values of less density areas.

**Application example:**

To demonstrate some first results from the proposed method a typical concrete ultrasonic testing problem is selected. The examination of tendon ducts in concrete buildings like bridges is very prominent because other techniques like radar cannot look inside metal sheets, but the interior of a tendon duct - especially the presence of air - is very important for the quality assurance of new or old buildings. Figure 3 shows a sketch of the examined part of a tendon duct used to carrying the roof of a large hall which hangs at some bridge-like outer skeleton built out of concrete. Strings within the vertical tendon ducts are used to carry the roof and some horizontal tendon ducts are used to pretension the concrete beam itself.

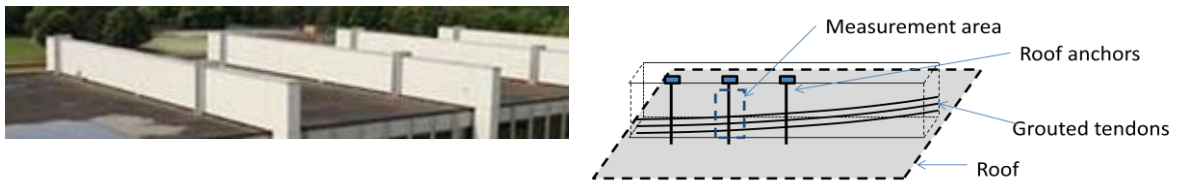


Figure 3: Left: roof of the building with roof anchors. Right: principle sketch of the measured arrangement. Diameter of the anchor ducts: 4cm, depth 10.5cm

For testing purposes a completely scanned data set along a tendon duct was used. By selecting single A-scans from the full measurement the interactive capabilities of the software may be repeatedly examined. Figure 4 shows an intermediate step of the processing: data are collected interactively, the result of the imaging with given frequency range, density of measurement points, assumed beam opening and test scatterers are displayed. The orientation of the roof anchors is displayed horizontally.

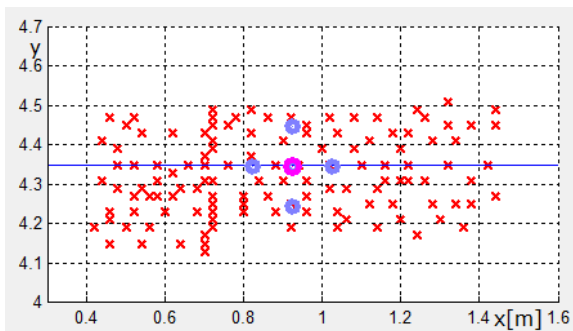


Fig 4a: Collection of 126 measurement points in a 2D area around the expected reflector

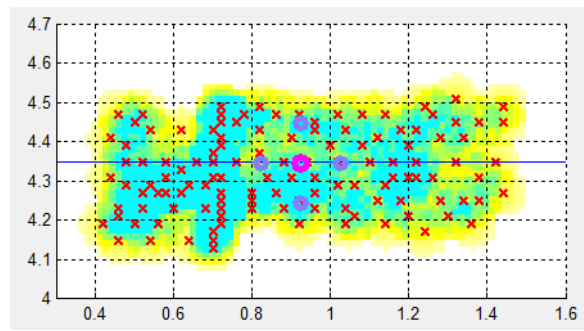


Fig 4b: Indication of the density of the captured data

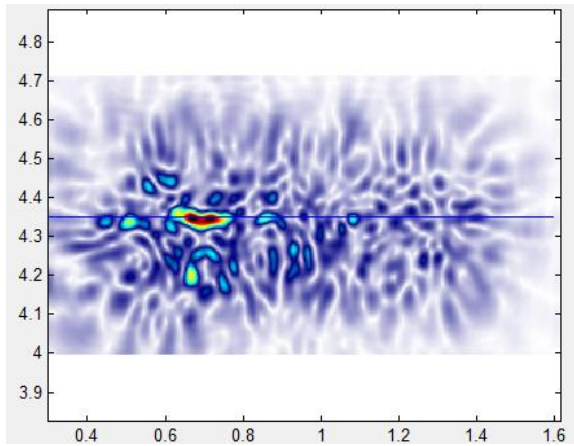


Fig 4c: SAFT - c-image of the data in the depth of the tendon duct. Frequency range 10-85kHz, 126 points

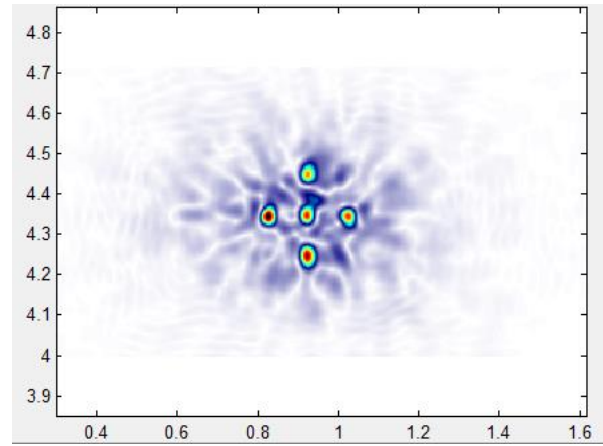


Fig 4d: SAFT - c image of a test arrangement of point scatterers (position s. fig. 4a) in the depth of the tendon duct. Frequency range 10-85kHz, 126 points

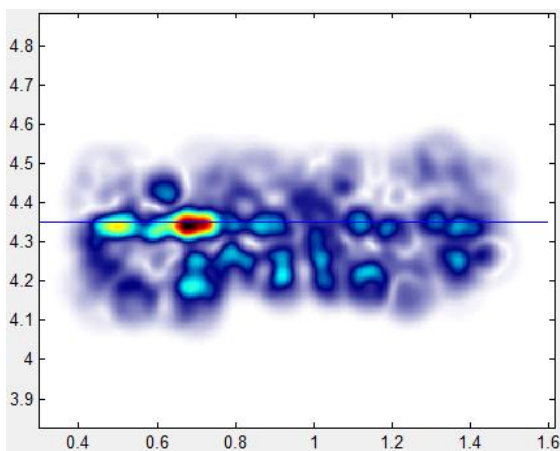


Fig 4e: SAFT - c-image, reduced beam opening angle (half width:  $30^\circ$ ) (reconstruction parameter), 126 points

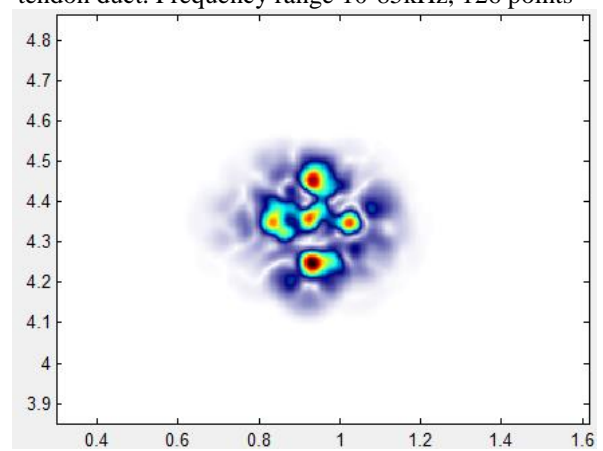


Fig 4f: SAFT - c-image of the test arrangement, reduced beam opening angle.

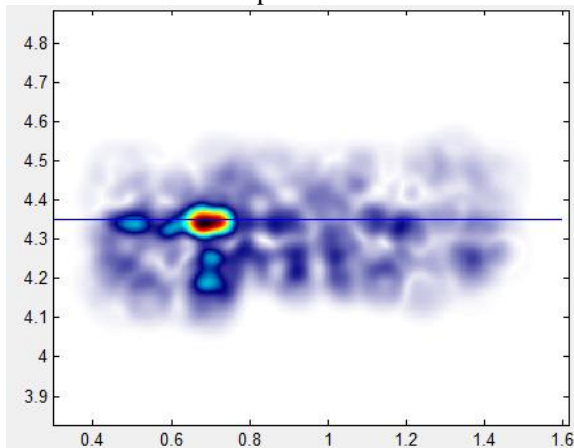


Fig 4g: SAFT - c-image, parameters like fig. 4e), equal weight for all A-scans, 126 points

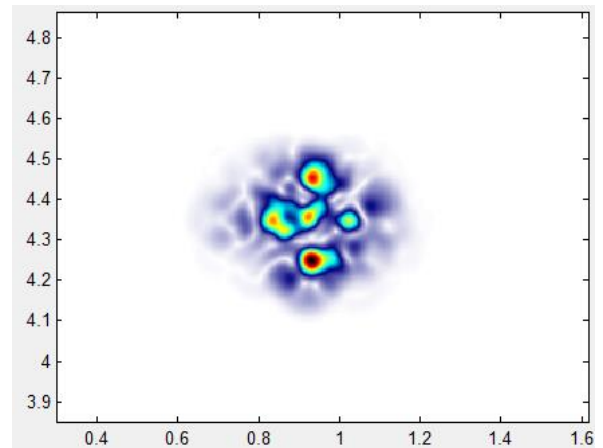


Fig 4g: SAFT - c-image of the test arrangement, reduced beam opening angle, equal weight

Figure 5 shows the SAFT reconstruction of the full scanned area with 1176 measurement points and a scanning distance of 0.02m. This comparison shows, that even for about 1/10 of points a rough overview and a characterization is possible.

Beside the amplitude of the reconstructed image a phase analysis of the reflection indications can be done, which can help to classify the type of the scatterer [16].

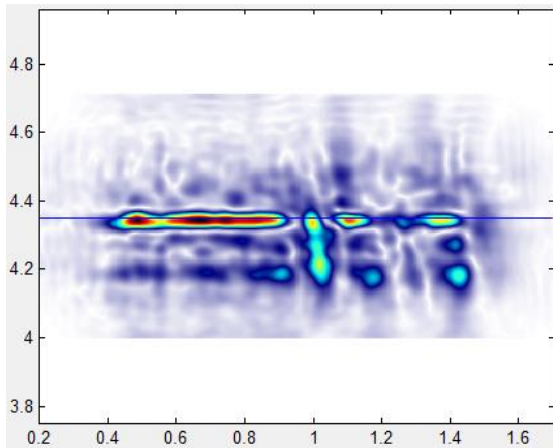


Fig 5a: SAFT - c-image, using full scanned dataset (half beam width: 90°, scan distance 0.02m, 1176 points)

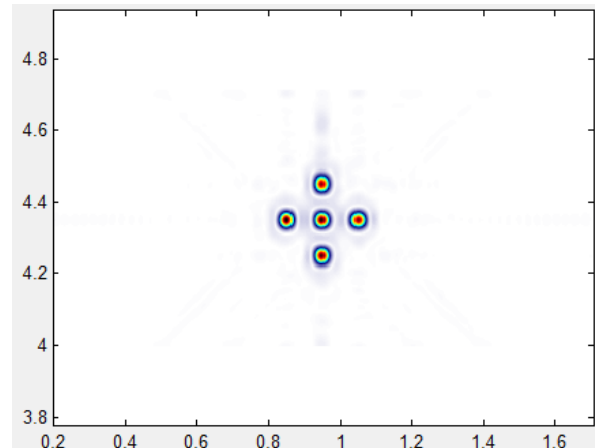


Fig 5b: SAFT - c-image, of the test arrangement, using positions of full scanned dataset (half beam width: 90°, scan distance 0.02m, 1176 points)

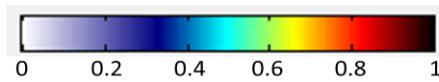


Fig 5c: Color scale used for all images. Each image is normalized to its own maximum

## Conclusion

The newly proposed method of performing imaging algorithms and defect classification by manually captured ultrasonic data gives promising preliminary results. The application possibilities cover all fields of ultrasonic testing, where the detection and classification quality in respect to the measurement effort is more important than a high quality reconstructed image achievable only by a scanning measurement.

Especially for NDT in CE nearly all practical applications on site demand special considerations because every building or structure is an “individual”. Mostly a test on site is necessary in order to decide if a NDT task may be solved by means of ultrasonic imaging. For this the new developed possibility to start 3D ultrasonic imaging (even including phase analysis) without scanning equipment or time consumable drawing of a measuring grid may offer a high potential.

The small size ultrasonic system with automated measuring of transducer location and calculation of SAFT reconstruction with measuring points, which do not have to be equidistant will reduce the effort for NDT application tests. The cumulative imaging will be an enormous progress in order to optimize the effort on site.

The new possibilities may help to make ultrasonic imaging available for more small and intermediate engineering offices.

In a future step of the development, the signal characterization and the imaging result will be combined, so that the operator can interactively make the decisions.

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