ABSTRACT

Synthetic aperture focusing technique (SAFT) has been known since late 70s when it was introduced and evaluated in the application to nuclear power plants by Southwest Research Institute. In theory, SAFT is capable of realizing the theoretical resolution potential of ultrasonic waves and considerably improving the signal-to-noise-ratio of the ultrasonic image of coarse-grained materials. In its most often implemented version based on delay-and-sum operations in time, SAFT mimics an acoustic lens used for focusing ultrasonic beams at a desired point in the region of interest.

However, the frequency-domain implementations of the synthetic aperture technique, developed in radar and seismology, offer substantial advantages in terms of performance and computational effort.

This paper presents results obtained using a frequency-domain implementation of SAFT inspired by the migration concepts used in seismology. The general structure of the algorithm based on the phase-shift operation in the frequency-wavenumber domain is outlined first. The proposed algorithm can be applied for layered media, which means that it is suitable both for contact and immersion ultrasonic inspection.

A brief theoretical introduction is followed by the presentation of evaluation results. The algorithm was applied for post-processing of ultrasonic data acquired in inspection of coarse grained metals (copper). The evaluation is made using the ultrasonic data obtained from the inspection of test specimens with artificial defects (side drilled holes and flat bottom holes). The performance of SAFT expressed in terms of its spatial resolution and grain noise suppression is studied.

INTRODUCTION

SAFT is a post-processing technique that is used to improve the lateral resolution of B-scan images, thereby improving the localization and sizing accuracy of defects. Due to the coherent averaging over several A-scans that takes place in SAFT, the processing also leads to grain noise suppression. Furthermore, the time-delay compensations that constitute the basic operations in SAFT automatically give a geometrical correction of the image. In essence, SAFT improves several image quality factors that are relevant in an ultrasonic inspection.

SAFT is the ultrasonic version of techniques that were originally developed in radar, sonar, and seismology, in which the corresponding names are synthetic aperture radar and sonar (SAR and SAS) and migration, respectively. SAFT has been mostly implemented in the space-time domain using delay-and-sum (DAS) operations whereas in SAR, SAS, and migration the implementations are almost exclusively in the frequency domain, there often referred to as the $f-k$ method.

With no approximations present, the time domain and frequency domain implementations would yield identical results. The main benefit of frequency domain implementations is that they offer an improved computational efficiency compared to DAS. A few exceptions of the use of frequency domain SAFT implementations in NDE can be found in [1,2,3].

SAFT is particularly well suited for scenarios where the sound speed is constant throughout the test object since this gives simple calculations of the time delays associated with the scatterers in question. This holds for contact testing of isotropic and homogenous objects but not for the case of immersion testing. In the latter case, the refraction at the boundary between the water and the test object must be taken into account and the calculation of the time delays introduces an additional computational effort in the algorithm. For instance, finding the propagation time between two points separated by one refracting interface involves solving a fourth order equation. Note also that the conventional $f-k$ methods are based on an assumption on constant wave velocity and the conventional frequency domain solutions do therefore not provide a solution to the problem either.
However, a scenario with layered structures having different sound velocities often occurs in reflection seismology where an approach that is strongly related to but not equivalent to SAFT, called migration, has been developed [4]. Unlike SAR and SAFT, migration makes explicit use of the wave equation in the processing. By viewing the measured signals at the sensors as a boundary condition for the wave equation, the field can be extrapolated both forward and backward in time and space. By essentially "turning the clock back", the field is back tracked to the scattering points.

One frequency domain version of migration that is particularly well suited for the immersion test problem was reported in [5]. The method is called phase shift migration and it is based on the assumption that the involved media are homogenous in the lateral direction but inhomogeneous in depth. The approach has recently been used also in ground penetrating radar [6] in which the problem of having different wave velocities in air and soil must be treated and for which the conventional SAR methods are inadequate.

In this work we investigate phase shift migration for imaging data acquired using immersion testing. The considered application is immersion testing of copper specimens of a similar type that will be used for the final disposal of Swedish spent nuclear fuel. The experiments aims at demonstrating the potential of phase shift migration for this application.

ALGORITHM OVERVIEW

The general idea in phase shift migration is to use the wave equation to extrapolate the field at different depths in the object. The data that that is acquired with the transducer scanned at depth $z=0$ constitutes the boundary condition required in these calculations. Loosely speaking, we calculate what measurements we would have obtained if the scanning had been performed with the transducer at a number of depths, different from $z=0$. This field extrapolation is performed using a frequency domain phase shift operation.

Suppose that we have extrapolated the field at $z > 0$ and consider the field reflected from a scatter located at the same depth. With the scatterer and the (hypothetical) scanning line having no depth separation, the propagation time between transducer and scatterer will be zero. Moreover, the field originating from that scatterer will be minimally spread laterally at time $t=0$. Therefore, by extracting the line corresponding to time $t=0$ from the extrapolated field at each depth, we will obtain a high resolution map of the objects interior.

An overview of the algorithm that implements the above given idea is presented in Fig. 1 and the computational steps indicated by the numbers are further detailed in the list below. Derivations and more algorithmic details can be found in [5,6].
1. Preprocessing: Each A-scan is matched filtered with the transducer impulse response in order to compensate for the phase delays caused by the transducer. These delays would otherwise distort the reconstruction.

2. A 2D Fourier transform with respect to \(x\) and \(t\) is performed on the B-scan resulting from the matched filtering: 
\[
P(k_x, z = 0, \omega) = \int \int P_{MF}(x, z = 0, t)e^{-j\omega t}e^{-j\omega t} \, dx \, dt,
\]
where \(k_x\) and \(\omega\) are the \(x\)-component of the wave-number vector and the angular frequency, respectively. The Fourier coefficients corresponding to down-going waves are nulled out.

3. An image line is extracted for depth, \(z_{m+1}\), using the inverse transform:
\[
p(x, z_{m+1}, t = 0) = \int \int P(k_x, z, \omega) \, dk_x \, d\omega
\]

4. The field is extrapolated to the new depth, \(z_{m+1} = z_m + \Delta z\), where \(\Delta z\) is the spacing in the \(z\)-direction between the lines in the reconstructed image. The extrapolation is calculated as the phase shift:
\[
P(k_x, z_{m+1}, \omega) = P(k_x, z_m, \omega) \exp \left( j \sqrt{4 \omega^2 \over c_m^2 - k_x^2} \Delta z \right)
\]
where \(c_m\) is the velocity in the media between depths \(z_m\) and \(z_{m+1}\).

Note that all integrals are computed using the fast Fourier transform (FFT) using discrete data. Note also that the phase shift operation allows separate velocities to be used for each image lines and this allows for treating media that are inhomogeneous in depth.

**EXPERIMENTS**

Two experiments were performed. The first aimed at demonstrating the method's ability to treat a scenario with two scatterers residing in layers having different velocity. This experiment was performed with a copper block immersed in water and containing a number of side drilled holes. A wire target was placed in front of the block in water. In this way we created a scenario with scatterers present both in the slow water medium and in the fast copper medium. The second experiment aimed at demonstrating how the method improves the resolution in C-scans and at the same time suppresses grain noise. The test object in this experiment was a copper block with flat bottom holes.
Both experiments were performed using a 2.25 MHz planar circular transducer from Panametrics with 10 mm diameter. Data was acquired at 100 MHz sampling rate and the pitch was $\Delta x=1$ mm. With these parameter settings, spatial and temporal aliasing was avoided during data acquisition.

Copper block with side drilled holes

The immersion test setup used in the first experiment is shown in Fig. 2. The transducer was scanned along the x-axis and pulse-echo measurements were acquired at 210 x-positions separated by 1 mm. The inspected object was placed with its front surface in the horizontal plane.

The acquired data is presented in Fig. 3 as an envelope B-scan, obtained by Hilbert transforming the raw data. The strong front surface echo is seen at approximately $t=60$ ms corresponding to the water path of approximately 45 mm and the wire target can be seen at $x=110$ mm at about $t=50$ ms. A secondary echo from the wire is also seen at $t=70$ ms at the same scanning position. It corresponds to a sound path transducer-Cu-wire-Cu-transducer. The fourteen side drilled holes (SDHs) are seen as hyperbolic patterns at increasing depths.

The image obtained by phase shift migration is presented in Fig. 4. In this image, the responses from the SDHs are concentrated to small spots and the same holds for the wire target. Note that an automatic geometrical correction is obtained through the migration since the method takes into account the different velocities at different layers. For example, the wire target's distance between to the front surface of the block can be correctly measured in the image to be 7 mm. Note also that the lateral resolution of the SDHs are approximately equal throughout the entire object.
Figure 3: The B-scan from the copper block with SDHs and with a wire target in front of the upper surface.

Figure 4: Image obtained by phase shift migration. The hyperbolic patterns representing the SDHs and the wire target have been transformed to small spots with lateral resolution that is approximately independent of depth.

The diffuse spot centred at $x=110$ mm and $z=61$ mm corresponds the above mentioned double reflection Cu-wire-Cu. Since multiple reflections are not taken into account in the development of the method, such echoes generally lead to blurred artefacts as the one seen here.

The improvement in lateral resolution can be further examined in Fig. 5 where local profile plots for each SDH are shown both for the B-scan and the reconstructed image. These profiles were obtained by calculating the maximum amplitudes within a depth interval covering each hole and projecting the values onto the $x$-axis. For instance, the profile of the SDH at $x=100$ was obtained using data in the rectangle defined by $x$ in the interval $[93,107]$ mm and $z$ in $[82,84]$ mm. For ease of comparison, the profiles have been normalized to have the same maximum amplitudes. Inspection of the profiles shown in the figure confirms the conclusion that the lateral resolution in the reconstructed image is practically independent of the depth. This holds also for the wire target which is surrounded by a medium with a different sound velocity than the SDHs.
Copper block with flat bottom holes

In the second experiment we performed a volume scan of a copper block with flat bottom holes (FBHs). The dimensions of the block are given in Fig. 6. The purpose of the experiment was to illustrate the improvements in detectability and lateral resolution that can be achieved through the method. The block had a grainy structure that caused both grain noise and sound attenuation causing the responses of the FBHs to be relatively difficult to detect in standard B-scans. Only the 4 mm diameter FBH gave a response that was easily detected in those images.

Figs 7 and 8 show two examples of envelope B-scans from the data set. The first shows a cross section over the 1 mm and 4 mm FBHs. The 1 mm hole cannot be seen at all but the response from the 4 mm FBH can be seen at $x=82$ mm and $t=82$ s. Note that the width of the response is approximately 15 mm. Fig. 8 shows a cross section over 2 mm and 3 mm and we can see weak responses from these holes at around $t=82$ s, at $x=18$ mm and $x=80$ mm, respectively.
Figure 7: B-scan acquired at \( y = 18 \text{ mm} \) passing over the 1 mm and 4 mm FBHs.

Figure 8: B-scan acquired at \( y = 63 \text{ mm} \) passing over the 3 mm and 2 mm FBHs.

In Fig. 9 the migrated image corresponding to the B-scan in Fig. 7 is presented. The 4 mm FBH at around \( z = 97 \text{ mm} \) is here reduced to approximately 5 mm.
In a similar way, the migrated image corresponding to the B-scan in Fig. 8 is presented in Fig. 10. The 3 mm and 2 mm FBHs at around $z=97$ mm are better localized in the $x$-direction thus providing better conditions for extracting a C-scan. Moreover, by comparing Figs 7 and 8 with Figs 9 and 10 we see that the migration results in suppressed grain noise.

A C-scan image showing a cross section of the block at a $z$-interval [95,99] mm, corresponding to 53-57 mm in the Cu-block, is presented in Fig. 11. The C-scan was obtained by projecting the maximum amplitude value within the given interval onto the $x$-$y$ plane. This C-scan should be compared to the C-scan shown in Fig. 12, which was created using B-scans that were migrated in the $x$-direction. The FBHs of diameters 2, 3, and 4 mm are visible in both images but the resolution is much improved in the migrated C-scan. Note that the improvement in resolution only concerns the direction of migration; the resolution in the $y$-direction is approximately the same in both images.
A number of profile plots covering cross-sections over the FBHs are shown in Fig. 13.
Figure 13 - Profile plots based on migrated data. Each profile has been normalized to have unit maximum amplitude. The two upper plots show profiles taken along the \( x \)-axis, in which migration was performed, and the lower show profiles in the \( y \)-direction.

**CONCLUDING REMARKS**

Phase shift migration has been proposed for ultrasonic imaging of objects immersed in water and the algorithm has been demonstrated to correctly treat the complication of having different sound velocities in the media and to yield images with a high lateral resolution under such conditions.

The experiment with the copper block with SDHs showed that the lateral resolution in the reconstructed image is practically independent of depth. It was also demonstrated using data from a block with FBHs that the phase shift migration along with the resolution improvement helps in suppressing grain noise and thus is a useful tool for the detection of defects that are buried deep in grainy materials.

The algorithm is implemented using FFT routines and the current implementation allows processing of the B-scans that takes less time than the data acquisition and we should note that the algorithm can still be speeded up significantly since the current implementation does not exploit that the acquired signals are relatively narrow band which means that a large number of Fourier coefficients can be neglected in the calculations.

The phase migration technique requires the knowledge of the sound velocities in the different media involved in the test. We have here considered only the two media water and copper but there are no principal restrictions on how many layers we can treat using the method as long as they are all horizontal. It is of course important to supply the algorithm with the correct velocity values and incorrect values will lead to both poor resolution and poor geometrical correction of the images. Fortunately, accurate velocity values can often be obtained relatively easily by combining information on the test object's dimensions with geometrical echoes such as front and back surface echoes.

**REFERENCES**


