Ultrasonic Imaging of Immersed Objects using Migration Techniques

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Abstract

The synthetic aperture focusing technique (SAFT) is often used for imaging in non-destructive ultrasonic testing. Conventional SAFT is well suited for contact testing of homogeneous objects because of the constant sound speed throughout the media, whereas the refraction present in the practically important case of immersion tests has so far prevented a widespread use of SAFT for such data. Fortunately, the problem of imaging layered objects has been extensively treated in geophysics where migration is used routinely for this kind of problems. This paper shows how such techniques can also be successfully applied to data from ultrasonic immersion tests.

1 Introduction

Non-destructive testing (NDT) using pulse-echo data have much in common with synthetic aperture radar (SAR) and sonar (SAS) and the synthetic aperture focusing technique (SAFT) was developed partly inspired by SAR and SAS. SAFT is usually implemented in the time domain using standard delay-and-sum operations and the required propagation delays are in the most basic form based on the assumption of constant sound speed throughout the medium.

This assumption is valid for contact testing of isotropic homogeneous materials but it does not hold for immersion tests. Due to the refraction that occurs at the interface between water and the test block, the propagation delays become more difficult to compute. These difficulties have prevented a widespread use of SAFT for immersion tests and, as a consequence, the advantage of SAFT of providing depth-independent lateral resolution has not been exploited for immersion test data. This is unfortunate since immersion tests are often more practical to perform than contact scans. One of the main reasons for this is that the water provides a uniform acoustical coupling between transducer and medium, something that may be difficult to achieve in a contact scan, because of rough surfaces of the scanned test block.

Migration techniques developed for processing of seismic exploration data and in particular phase shift migration provides simple and elegant means to treat the difficulties caused by refraction. The idea leading to the migration algorithms are somewhat different than the spatio-temporal matched filtering viewpoint that is perhaps dominating in SAR, SAS, and SAFT. In migration, the scanned data is considered as a measured field from a set of "exploding reflectors" in a medium having half the sound speed as in the physical medium, and the wave equation is used explicitly to extrapolate this field to depths different from the sensor plane. Image lines at these depths are obtained by reading out the corresponding field at time $t = 0$, which is called "imaging condition" for this scenario. In this paper, it is shown how phase shift migration can be successfully applied to data from ultrasonic immersion tests.

The paper starts by noting some differences between ultrasonic testing and seismic exploration. This is followed by a brief summary of the phase shift migration algorithm. A number of illustrative examples on how to apply migration to ultrasonic immersion test data under various conditions are then given, followed by a summary.

2 Comparison between ultrasonic immersion tests and seismic exploration

Although both ultrasonic testing and seismic exploration are based on pulse-echo measurements acquired at several positions, there are differences between the two scenarios. Some of these are listed below.

In seismic exploration, the firing of a pulse is expensive and to maximize information gained at each shot, an array of sensors is typically used at reception. Although ultrasonic testing can be performed in a similar way, the normal operation is presently to use a single transducer.

In NDT, the operator typically can get precise information about the sound speed within water and test block, either from tables or through separate experiments. In seismic exploration, the sound speeds in the different earth layers are unknowns that are estimated using information supplied by the array measurements.

In seismic exploration it is difficult to directly measure so-called zero-offset data, i.e., data acquired with the receiving sensor being at the same spot as the transmitter. Such zero-offset signals are instead synthesized by performing so-called normal move-out using the array data. In ultrasonic testing, the transducer acts both as a transmitter and receiver and zero-offset data is trivial to obtain.

In seismic exploration the wavelength is typically large compared to the sensor size whereas in NDT, the transducer diameter, D, may be a few wavelengths. As in SAR, the transducer size limits the achievable lateral resolution to approximately $D/2$. Note that a positive consequence of the finite sized transducer is that the spatial sampling step can be as large as $D/4$ without experiencing spatial aliasing. For point-like sensors the maximum step is bounded by $\lambda/4$, which is more restrictive. [5]

3 Phase shift migration algorithm

Prior to phase shift migration, the raw data is preprocessed with a matched filter to compensate for unwanted phase delays caused by the transducer impulse response. This preprocessed data, below denoted by $s(t, x, y, z = 0)$, is further Fourier transformed, either in 3D or 2D, depending on whether it is a full area scan or a line scan. This yields the Fourier domain data for depth $z = 0$, denoted by $S(\omega, k_x, k_y, z = 0)$. The Fourier domain data is extrapolated to other depths, separated by Δz, using repeated multiplication by the phase shift factors, which in the 3D case is defined as

$$\alpha(\omega, k_x, k_y, \Delta z, c) = e^{-j\Delta z\sqrt{\frac{4\omega^2}{c^2} - k_x^2 - k_y^2}}, \quad (1)$$

where c is the sound speed at the current depth, ω is the angular frequency, and k_x and k_y are the wave numbers in x and y directions (the scanning plane), respectively.

At each depth, an image plane (in 3D) or line is extracted as the field at the imaging condition $t = 0$. This can be calculated as

$$Im(x, y, z) = \iiint S(\omega, k_x, k_y, z)e^{j(k_x x + k_y y)}dk_x dk_y d\omega. \quad (2)$$

Note that the computations can be organized as a summation over ω, followed by an inverse 2D or 1D Fourier transform.

The algorithm is schematically illustrated in **Figure 1**. Algorithmic details and derivations can be found in literature on migration. See for instance [3].

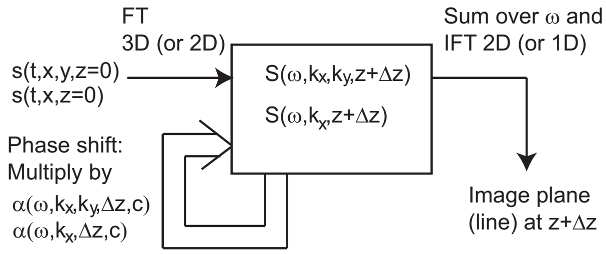

Figure 1: Schematic illustration of the phase shift migration algorithm.

4 Illustrative experiments

4.1 Basic 2D imaging

The first experiment illustrates the basic use of phase shift migration for objects immersed in water in a 2D case. The considered object is a copper block with a number of side drilled holes acting approximately as point scatterers. The measurement setup and the block is illustrated in **Figure 2**.

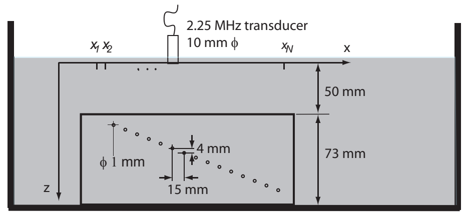

Figure 2: The measurement setup for immersion test of the copper block with side drilled holes.

In the reconstruction using phase shift migration, the sound speeds in water and copper were set to 1480 m/s and 4660 m/s, respectively. The reconstructed image is shown in **Figure 3** in which we see that the reconstructed holes have approximately the same lateral resolution throughout the object.

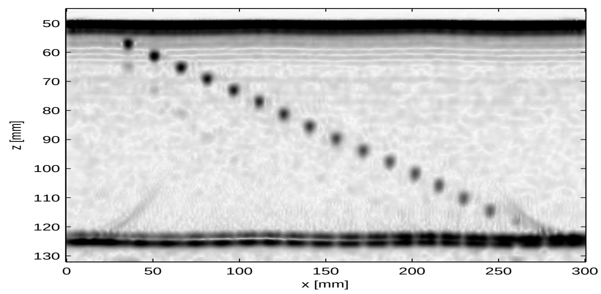

Figure 3: The reconstructed image.

4.2 Treating non-horizontal layers.

Phase shift migration requires in its basic form the velocity to be a function of depth only. This assumption is violated if the front surface of the immersed test object is non-planar, and variants of phase shift migration have been developed to treat more general velocity variations [4]. In NDT where the considered man made objects often are planar, the assumption can still be violated if the object is not placed parallel to the scanning plane. In practical applications it may be difficult to avoid some slight tilting and it is relevant in NDT to have means to robustly treat non-horizontal layers. Migration provides such simple means.

The idea is to migrate the field to a set of points placed on a line that is parallel to the front surface of the object. This transformed data fulfils the required assumptions of front surface and scanning plane being parallel and standard phase shift migration can be applied to this data.

The same copper block as in the previous experiments are used to illustrate the concept. The block was tilted approximately 2 degrees and the raw data is presented in **Figure 4**. The tilt-compensated data is presented in **Figure 5** and the resulting reconstructed image in shown in **Figure 6**. We see that the reconstructed image show very little difference from the image in **Figure 3** that was reconstructed under more ideal conditions.

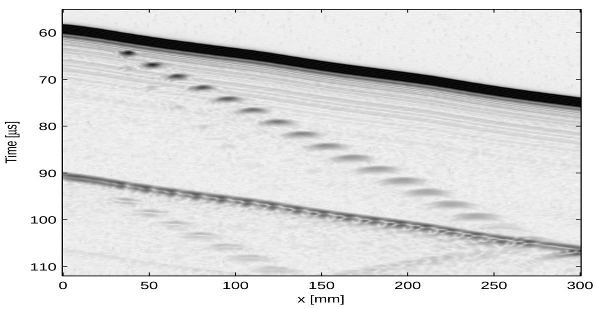

Figure 4: The raw data from a slightly tilted block.

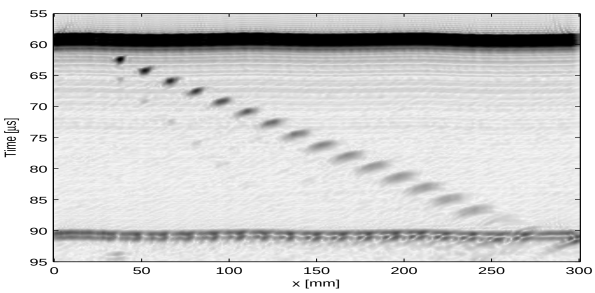

Figure 5: Data that has been compensated for the tilt using phase shift migration.

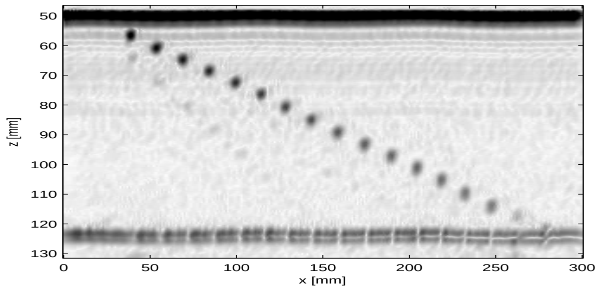

Figure 6: The results of phase shift migration of the tilted copper block.

4.3 Handling layered test blocks

Sometimes the test object itself consists of layers with different sound speeds. For instance, clad steel plates consist of steel covered with a protective layer of some suitable alloy. In this section we illustrate how a scenario with layered object can be treated using migration. It is illustrated using the copper block with side drilled holes considered earlier, and for practical reasons the additional layer was here made of gypsum. The layer was 8 mm thick and the sound speed was estimated to 2500 m/s.
The results of the migration are shown in **Figure 7**, where we can see that the reconstructed hole now are more distorted than in the previous experiments. The reason is most likely abberation caused by sound speed variations within the gypsum layer and/or poor adherence between gypsum and copper.

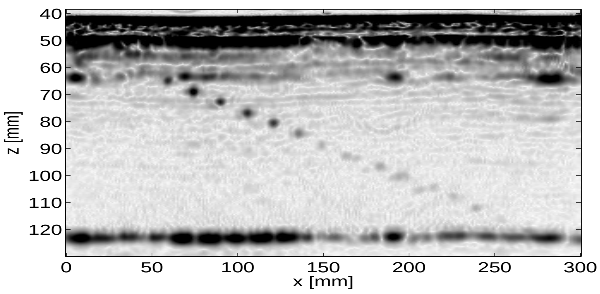

Figure 7: The results of phase shift migration of the copper block covered by a gypsum layer.

4.4 3D migration

3D data is obtained by scanning over a grid in the $x - y$ plane. Traditionally, the primary use of such scans has been to create so-called C-scans, which are cross section images from certain depth intervals of interest. Typically, the C-scans are obtained by extracting the maximum amplitude within the depth interval and geometrically focused transducers are used to achieve good resolution. Here we illustrate the use of phase shift migration on a 3D data set from a copper block with four flat bottom holes, with diameters 1-4 mm, see **Figure 8**. C-scan images are formed from the reconstructed data by extracting the maximum values within an interval of interest, in the same manner as C-scans are extracted from raw data.

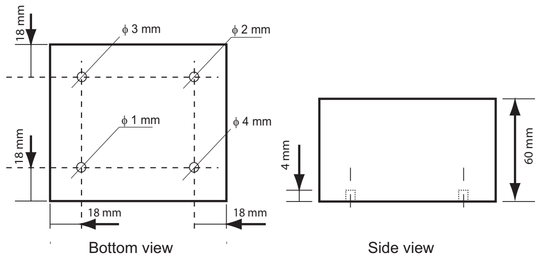

Figure 8: A schematic view of the copper block with flat bottom holes.

Figure 9 shows a C-scan extracted from the unprocessed data and **Figures 10** and **11** from a set of 2D reconstructed images and from the fully 3D reconstructed data, respectively. We note that the resolution improves in the x-direction in the C-scan from the 2D-reconstructed data, and that an overall significant improvement is achieved in the 3D case. The response from the 1 mm hole is too weak to be seen.

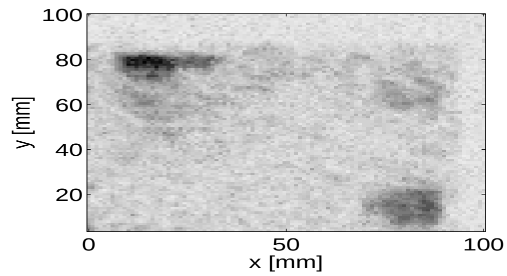

Figure 9: A C-scan extracted from the raw data. Note that only the 4 mm hole is clearly visible. The dark area where the 3 mm hole should appear consists mainly of disturbances from back wall echoes.

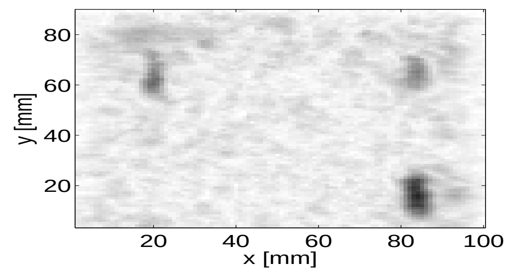

Figure 10: The results of 2D phase shift migration in the x-direction.

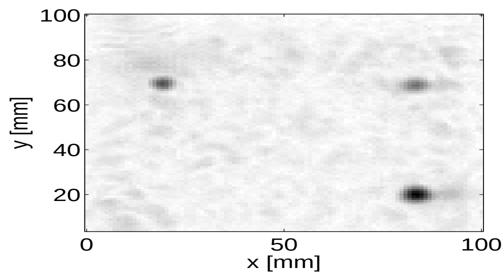

Figure 11: The results of 3D phase shift migration of the copper block.

5 Summary

This paper has illustrated the use of phase shift migration on ultrasonic pulse-echo data from objects immersed in water. We have pointed out some practical issues that may be of concern in NDT, in particular those concerning sloping front surfaces and multi-layered objects, and we have shown how to address these using migration.

References

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