Fast total focusing method for ultrasonic imaging

Ewen Carcreff[1,a)], Gavin Dao[2] and Dominique Braconnier[1]

[1]*The Phased Array Company, 9365 Allen road, West Chester, Ohio, USA*
[2]*Advanced OEM Solutions, 8044 Montgomery road 700, Cincinnati, Ohio, USA*

[a)]ewen.carcreff@thephasedarraycompany.com
[b)]gavin.dao@aos-ndt.com

Abstract. Synthetic aperture focusing technique (SAFT) and total focusing method (TFM) have become popular tools in the field of ultrasonic non destructive testing. In particular, they are employed for detection and characterization of flaws. From data acquired with a transducer array, those techniques aim at reconstructing an image of the inspected object from coherent summations. In this paper, we make a comparison between the standard technique and a migration approach. Using experimental data, we show that the developed approach is faster and offers a better signal to noise ratio than the standard total focusing method. Moreover, the migration is particularly effective for near-surface imaging where standard methods used to fail. On the other hand, the migration approach is only adapted to layered objects whereas the standard technique can fit complex geometries. The methods are tested on homogeneous pieces containing artificial flaws such as side drilled holes.

INTRODUCTION

Ultrasonic non destructive testing is a standard to detect and characterize flaws in industrial parts [1]. The emergence of array transducers [2] has put forward advanced imaging methods such as synthetic focusing techniques [3]. From an array transducer, the purpose is first to acquire data using single emitting elements. The synthetic aperture focusing technique (SAFT) is using mono-static acquisitions, *i.e.* each element acts in pulse-echo [4, 5]. The full matrix capture (FMC) approach corresponds to the multi-static case where a single element emits the wave and the reception is performed with all the elements [6]. The multi-static acquisition hence results in much more data than the mono-static case. The reconstruction is then applied on the capture data and has the same principle for the mono-static and multi-static cases. The standard approaches called SAFT and total focusing method (TFM) are based on coherent summations to generate the output image. This procedure is equivalent to focus at each point of the reconstructed image by computing the proper delays.

The advantages of this method is the freedom of defining the reconstructed image. The size and precision can be easily changed, which is not possible in conventional ultrasonic imaging. The other merit is the adaptability in terms of experiment geometries. Indeed, the delay laws can be calculated for various probes and piece geometries. The main issue is definitely the computational cost of the reconstruction algorithms. According to the output image size, the computation time can be prohibitive, in particular for real-time applications [7].

The migration approach has been introduced in the geophysics community by Stolt in the 1970's [8]. In the ultrasonic non destructive domain, implementations of SAFT [9] or TFM [10] have been proposed in the past years and have demonstrated interesting performances. This method proposes a elegant formulation of the inverse problem. The purpose of this paper is to compare the two approaches in terms of reconstruction quality and computational cost. The paper is organized as follows. Section 2 is presenting the standard and the migration approach for TFM. Then, they are compared in section 3 using experimental data acquired from an aluminum block containing side drilled holes. The section 4 gives conclusions of this work.

PRESENTATION OF THE METHODS

Standard TFM methods

The mono-static focusing method – known as SAFT – works with pulse-echo data for all elements of the transducer array [4, 5]. As illustrated in Figure 1a, each element is emitting and is receiving, and the operation is repeated for all elements. The data received by element i placed in u_i is denoted $y(t, u_i)$. If we consider N_{el} elements, the coherent

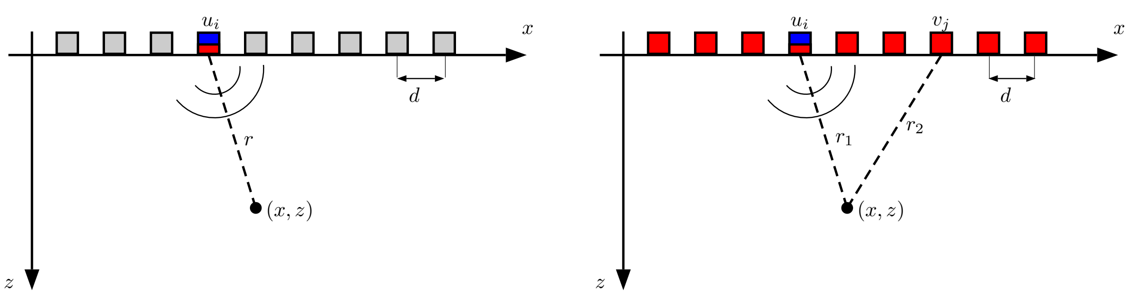

FIGURE 1. (a) mono-static acquisition. (b) multi-static acquisition (FMC). Emitting elements are in blue and receiving elements are in red.

summation for a reconstruction point (x, y) is performed by [3]

$$o(x,z) = \sum_{i=1}^{N_{el}} y\left(\frac{2r}{c}, u_i\right), \tag{1}$$

where $r = \sqrt{(x-u_i)^2 + z^2}$ is the distance between the element and the computation point and c is the wave velocity supposed constant. In practice, the data is sampled so that we take the closest value of $y(2r/c, u_i)$ or perform interpolation [11]. The full image **o** can be defined on various grids such as a Cartesian grid. The great advantage of TFM is the algorithm simplicity and the possibility to set freely the size and the precision of the grid, contrary to conventional ultrasonic imaging.

The multi-static focusing method or total focusing method (TFM) employs every transmitter-receiver pair of the array transducer as presented in Figure 1b. The A-scan acquired from emitter i and receiver j is noted $y(t, u_i, v_j)$. The reconstruction at point (x, y) is then achieved by [6]

$$o(x,z) = \sum_{i=1}^{N_{el}} \sum_{j=1}^{N_{el}} y\left(\frac{r_1 + r_2}{c}, u_i, v_j\right), \tag{2}$$

where $r_1 = \sqrt{(x-u_i)^2 + z^2}$ and $r_2 = \sqrt{(x-v_j)^2 + z^2}$. The amount of data and computational cost is much more important than for the mono-static case. This point is the main issue of TFM, which is difficult to apply in real-time applications. In recent years, works have been focused on parallelization through GPP or GPU [7]. However, the larger number of sums enables the reduction of the insignificant signals such as noise, which increases the signal to noise ratio. The TFM algorithm is a heuristic approach of the inverse problem but gives a reasonable approximation. Results on experimental are presented in the next section.

Migration TFM methods

Migration methods had been proposed in the Geophysics community in the 1970's [8]. They work in the wavenumber domain and had been applied for the mono-static [9] and the multi-static [10] cases. For mono-static TFM, we consider $Y(f, k_u)$ the transform of $y(t, u)$ in the wavenumber domain where k_u is the wavenumber along the element direction u. The principle is then to migrate $Y(f, k_u)$ in order to get $Y(k_x, k_z)$. To do so, we perform the variable change

$$\begin{cases} k_x = k_u \\ k_z = \sqrt{4\frac{f^2}{c^2} - k_u^2}. \end{cases} \tag{3}$$

This mapping is sensitive to errors and has to be effected by interpolation [11]. The reconstructed image $o(x, z)$ is finally obtained by getting back in the spatial domain by inverse transform of $Y(k_x, k_z)$. For the multi-static case, the wavenumber mapping is different because of the acquisition configuration:

$$\begin{cases} k_x &= k_u + k_v \\ k_z &= \sqrt{\frac{f^2}{c^2} - k_u^2} + \sqrt{\frac{f^2}{c^2} - k_v^2}. \end{cases} \tag{4}$$

Then, we have to sum the maps for all given k_u to get the map in the wavenumber domain

$$Y(k_x, k_z) = \sum_i Y(k_x, k_z \mid k_u(i)). \tag{5}$$

The migration approach results in a more elegant formulation of the inverse problem. The main issue of migration TFM is that it can only be considered for flat layered objects [12], contrary to the standard method that is more flexible. Moreover, the grid definition must fit with the element array, which make difficult to adapt the grid spans. Moreover, the standard approach usually applies limited apertures in order to reduce the sum number and hence lower the computation time. This trick is not directly transposable to the migration technique. Finally, another advantage of migration approach is the easier possibility to use filtering and regularization techniques [13].

RESULTS WITH EXPERIMENTAL DATA

Mono-static case

In this section, we give experimental results of the total focusing algorithms. The piece under test is an aluminum block shown in Figure 2a and is containing side drilled holed with 1 mm diameter. The piece is inspected using a contact array transducer with N_{el} = 128 and d = 0.5 mm, around 5 MHz.

(a) (b)

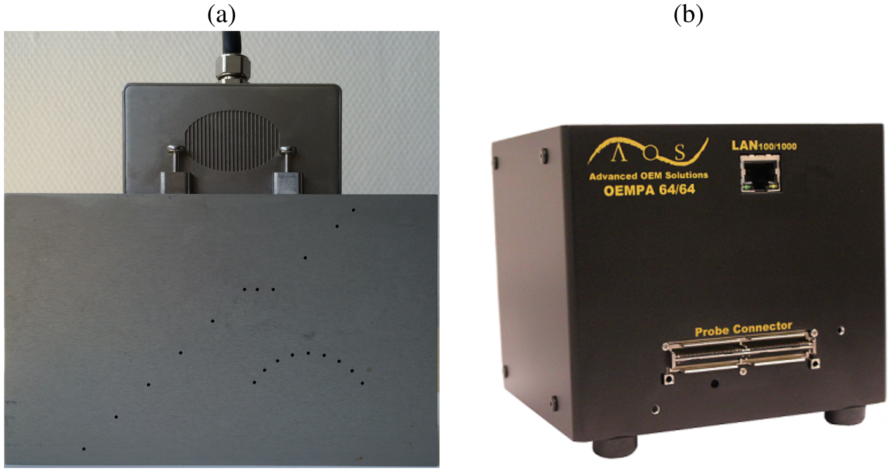

FIGURE 2. (a) Aluminum block with SDH ∅ 1 mm, (b) OEMPA phased array device.

The acquisition is performed using the OEMPA device [14], developed by the AOS company[1] and presented in Figure 2b. Those devices enables the full matrix acquisition in real-time with high precision. The reconstructed image size is set to 1024 × 1500 pixels and is presented in Figure 3. To facilitate comparisons, envelope processing with Hilbert transform has been performed on the output images. We have also normalized the amplitudes. The migrated image shows a better signal to noise ratio (SNR) than the standard image, of almost 30 dB. It also shows less diffraction

[1] See the website *www.aos-ndt.com*

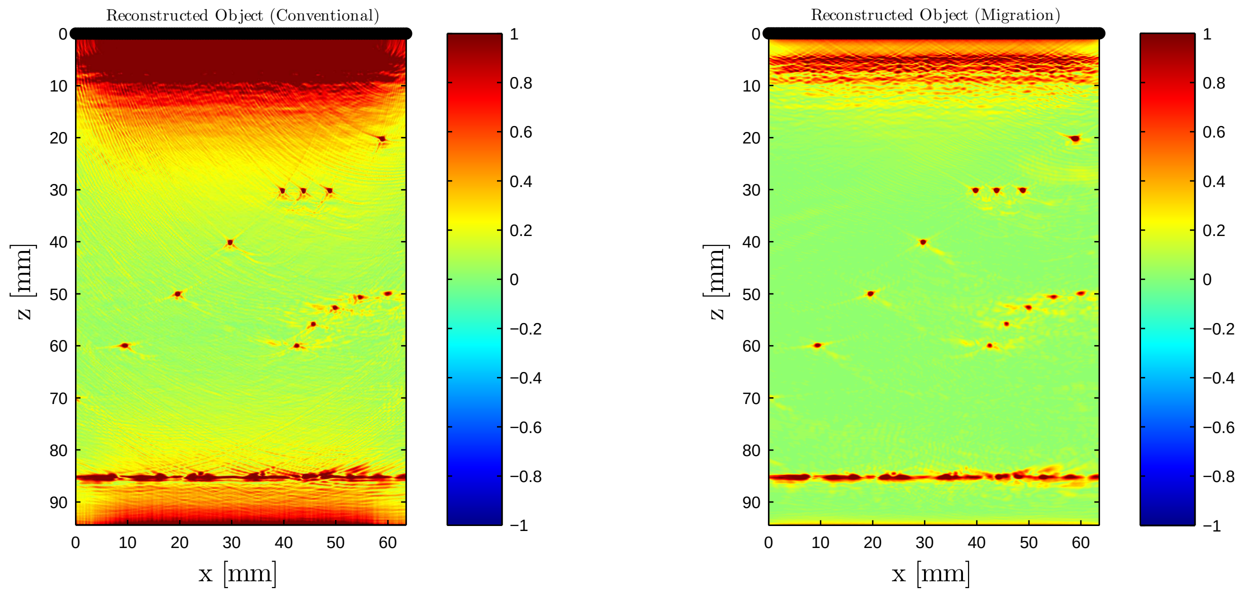

FIGURE 3. TFM images (1024 × 1500) for the standard and the migration approaches (mono-static). The element positions are plotted with full black rounds.

artifacts as it is clearly visible in the area of the holes in half-circle of the image in Figure 3. Moreover, note that migration permits a better near surface imaging. In table 1, the computation times for several output image sizes are displayed. There are much less important for the migration approach, up to around a factor 100. The migration computation times remain equivalent because the maps in the wavenumber domain keep the same size in order to respect the NyquistShannon sampling theorem. The final image is then obtained by interpolation in the x direction.

TABLE 1. Computation times in seconds (mono-static).

Size	standard	migration
1024×1500	16.61	0.17
512×1500	9.27	0.09
256×1500	4.22	0.08
128×1500	2.15	0.09

Multi-static case

In this part, the full matrix capture has been achieved with the same probe as previously but with $N_{el} = 64$ elements, resulting in $64 \times 64 = 4096$ A-scans. The results for a 512×1500 image are illustrated in Figure 4. As for the mono-static case, the SNR is higher for the migration image. Another key benefit of migration is the capacity to perform near-surface imaging. Indeed, the standard TFM approach exhibits a so called dead zone near the object surface that make imaging difficult. As illustrated in Figure 4, the migration approach is more robust to near surface imaging. The standard approach also gives more diffraction artifacts around the holes, that is more visible in a zoom on the three close holes realized in Figure 5. We also plot the vertical and horizontal lines corresponding to the three holes in Figure 6. The SNR of the migration result is higher than the standard one, by $40 \sim 50$ dB. Moreover, the resolution of the three detected holes is clearly enhanced with the migration technique, which helps to better distinguish the three flaws. Other results appear in a previous work [15], where we show results from oriented slits in a aluminum block. The computation times related to muti-static processing are presented in table 2. Those times are logically greater than for the mono-static processing. The migration processing is obviously faster than the standard approach, up to a factor

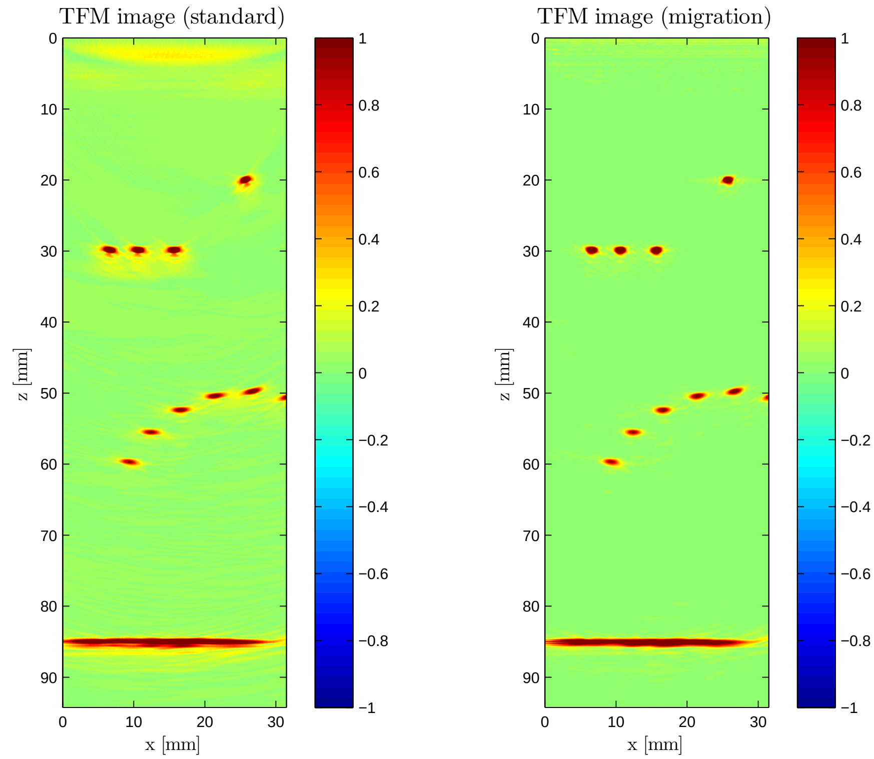

FIGURE 4. TFM images (512 × 1500) for the standard and the migration approaches (multi-static).

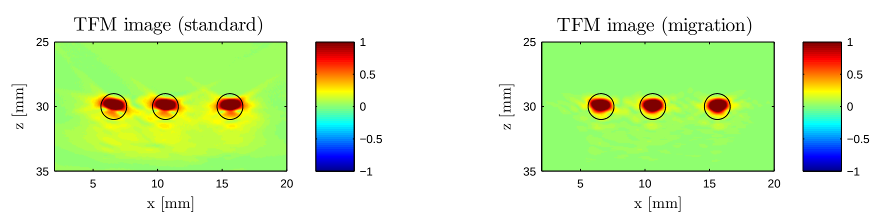

FIGURE 5. Zoom of Figure 4 on the three close holes (diameter 1 mm). The contour of the flaw is plotted in black line.

50 in the presented example. As for mono-static, the migration computation time remains approximately constant because the core algorithm is applied to constant size images. The difference comes from the final interpolation applied along x direction.

CONCLUSIONS

This work has presented total focusing methods for ultrasonic array imaging. Two approaches have been implemented and tested on experimental data: the standard and the migration approaches. From data acquired with an aluminum block containing side drilled holes, we have shown that the migration approach has a higher signal to noise ratio and less diffraction artifacts than the standard approach. In particular, the migration method is efficient for near surface imaging where standard techniques used to have a dead zone. Moreover, the migration approach has a smaller computation time compared to standard TFM, which demonstrates the great potential of this method in real applications.

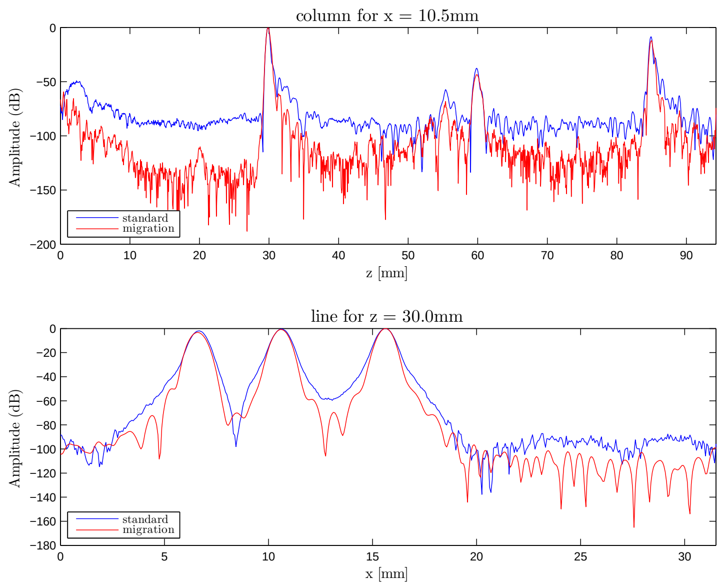

FIGURE 6. Resultst of multi-static TFM: lines for x = 10.5 mm and z = 30.0 mm.

TABLE 2. Computation times in seconds (multi-static).

Size	standard	migration
1024×1500	719.06	14.03
512×1500	353.29	12.63
256×1500	177.76	12.16
128×1500	91.29	12.34

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