Comparison of conventional technique and migration approach for total focusing

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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 conventional technique and a migration approach. Using synthetic and experimental data, we show that the developed approach is faster than the conventional total focusing method but is less flexible. Indeed, the migration approach is 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.

1 Introduction

Ultrasonic non destructive testing is a standard to detect and characterize flaws in industrial parts [7]. The emergence of array transducers [1] has put forward advanced imaging methods such as synthetic focusing techniques [11]. 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 [6, 9]. 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 [4]. 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 conventional 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 [8].

The migration approach has been introduced in the geophysics community by Stolt in the 1970's [13]. In the ultrasonic non destructive domain, implementations of SAFT [12] or TFM [5] have been proposed in the past years and have demonstrated interesting performances. 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. The section 2 is rapidly presenting the methods. Then, they are compared in section 3. The section 4 gives conclusions and future works.

2 Presentation of the methods

2.1 Conventional TFM methods

The mono-static focusing method – known as SAFT – works with pulse-echo data for all elements of the array transducer [6, 9]. As illustrated in figure 1, 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 summation for a reconstruction point (x, y) is performed by [11]

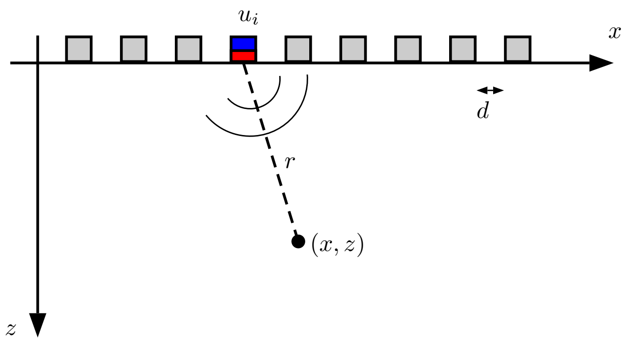

Figure 1: Concept of the mono-static capture (SAFT). Each single element is emitting (in blue) and is receiving the signal (in red).

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

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 [3]. The full image $\mathbf{o}$ 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 employs every transmitter-receiver pair of the array transducer as presented in figure 2. The A-scan acquired from

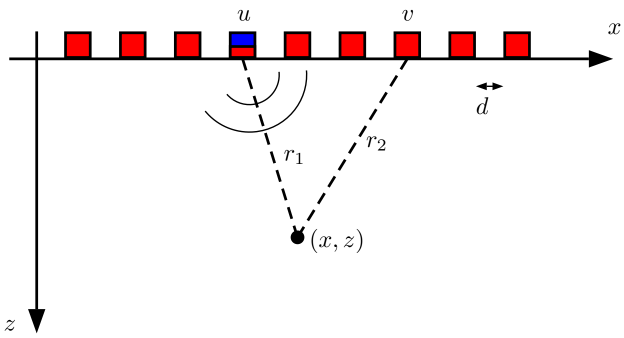

Figure 2: Concept of multi-static capture (full matrix capture). A single element is emitting (in blue) and the signals are received by all transducers (in red).

emitter i and receiver j is noted $y(t, u_i, v_j)$. The reconstruction at point (x, y) is then achieved by [4]

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

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 the recent years, works have been focused on parallelization through GPP or GPU [8]. 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.

2.2 Migration TFM methods

Migration methods work on the wavenumber domain [2, 13]. This method has been applied for the mono-static [12] and the multi-static [5] cases. For mono-static TFM, we consider $Y(f, k_u)$ the Fourier transform of $y(t, u)$ 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 $Y(k_x, k_z)$. This mapping is sensitive to errors and has to be effected by interpolation [3]. The reconstructed image $o(x, z)$ is finally obtained by inverse Fourier transform of $Y(k_x, k_z)$. For the multi-static case, we have to sum the maps for all given k_u, $Y(k_x, k_z \mid k_u)$, to get the map in the wavenumber domain.

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 [10], contrary to the conventional 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 conventional 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.

3 Results with experimental data

3.1 Mono-static case

In this section, we give experimental results of the total focusing algorithms. The piece under test is made of aluminum showed in figure 3 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. The reconstructed image size is set to 1024×1500 pixels and

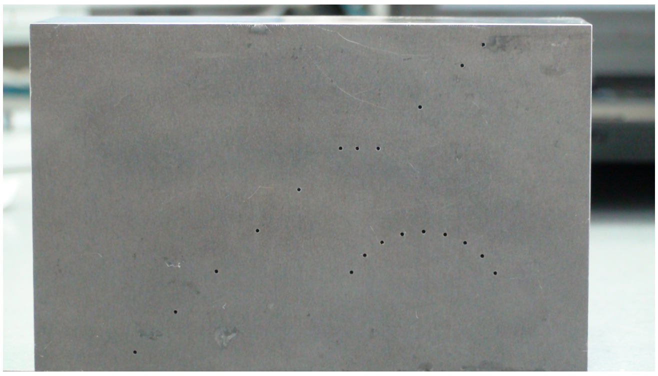

Figure 3: Photo of the inspected aluminum piece.

is presented in figure 4. To facilitate comparisons, envelope processing with Hilbert transform has been performed on the output images. The conventional image exhibits a lower signal to noise ratio (SNR) than the migration result and diffraction artifacts. On the other hand, the migrated image shows better SNR, of almost 30 dB. If we look at the vertical and horizontal lines of the center hole (30 mm, 40 mm) plotted in figure 5, we observe the higher SNR for the migration ap-

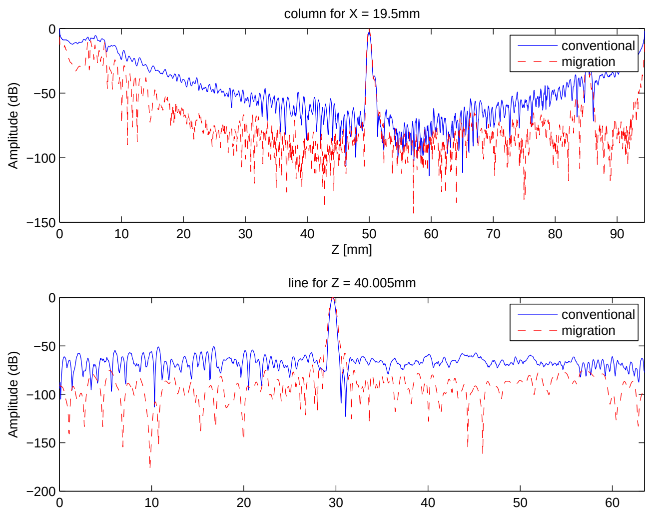

Figure 5: Resultst of mono-static TFM: lines for $x = 19.5$ mm and $z = 40.0$ mm.

proach in both directions. It it also clearly visible in the area of the holes in half-circle of the image in figure 4.

In table 1, the computation times for several output image size are displayed. There are much less important for the migration approach, of around a factor 10.

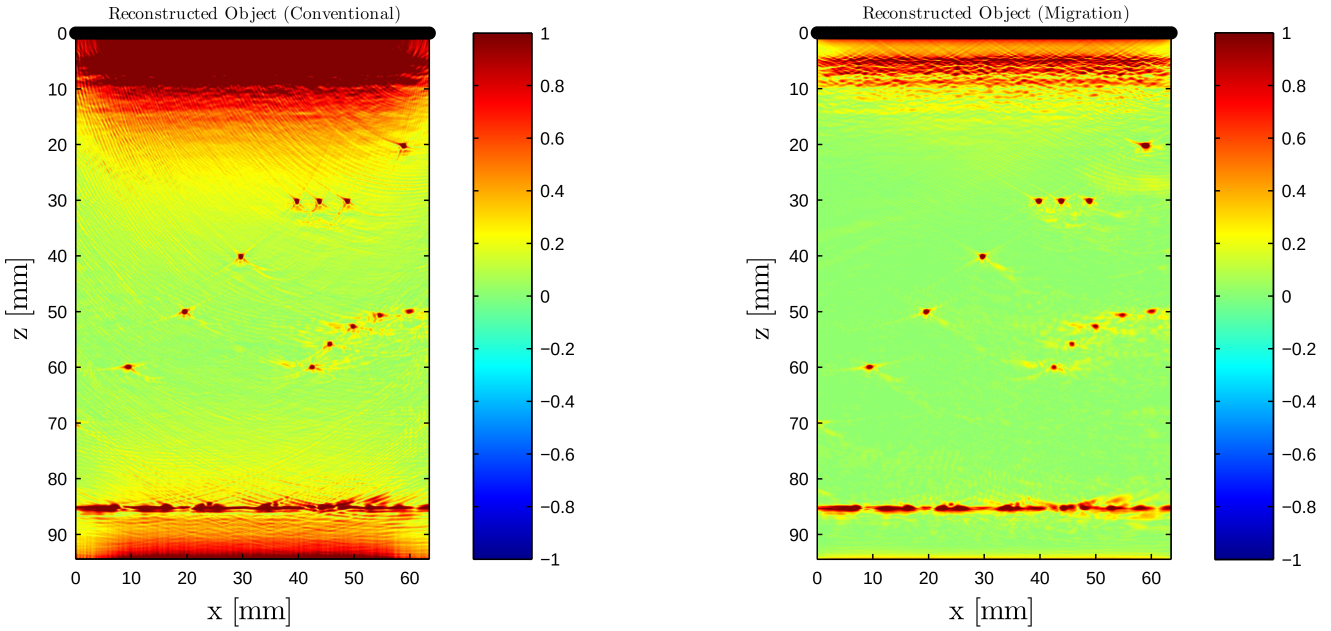

Figure 4: Results of TFM image for the conventional and the migration approaches (mono-static). The element positions are plotted with full black rounds.

Size	conventional	migration
1024×1500	17.67	2.74
512×1500	8.47	0.77
256×1500	4.49	0.26
128×1500	2.05	0.17

Table 1: Computation times in seconds (mono-static).

3.2 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 6. As for the mono-static case, the SNR is higher for the migration results. In particular, artifacts appear around the flaws for the conventional method. We also plot the vertical and horizontal lines corresponding to the three holes. The SNR of the migration result is higher than the conventional 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.

The computation times related to muti-static processing are presented in table 2. Those times are logically greater than

Size	conventional	migration
512×1500	332.8	176.4
256×1500	166.0	43.1
128×1500	83.0	10.9

Table 2: Computation times in seconds (multi-static).

for the mono-static processing. The migration processing is obviously faster than the conventional approach, of a factor between 2 and 8 in the presented example.

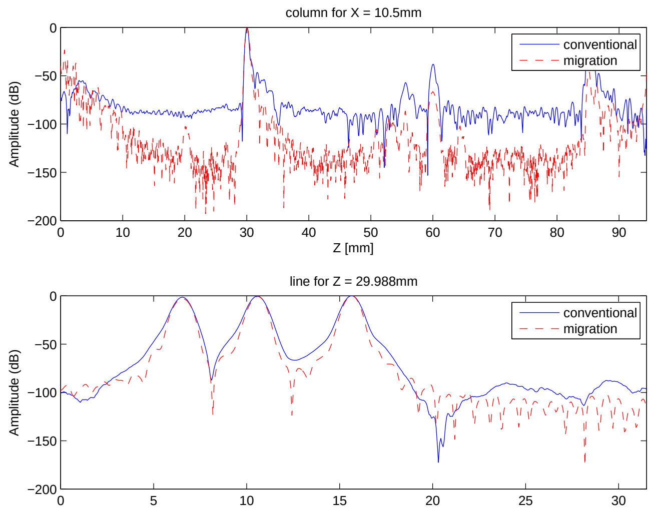

Figure 7: Resultst of multi-static TFM: lines for $x = 10.5$ mm and $z = 30.0$ mm.

4 Conclusions

This work has presented the total focusing method for ultrasonic array imaging. Two approaches has been implemented and tested on experimental data: the conventional and the migration approaches. The migration TFM has shown a higher signal to noise ratio and a smaller computation time, which demonstrates the great potential of this method in real applications. This approach is nevertheless not as flexible as the conventional modality. Indeed, it is devoted to layered objects – such as flat immersed parts –, and can not be applied to more complex geometries. Future works could consider a real-time implementation of the migration approaches of TFM.

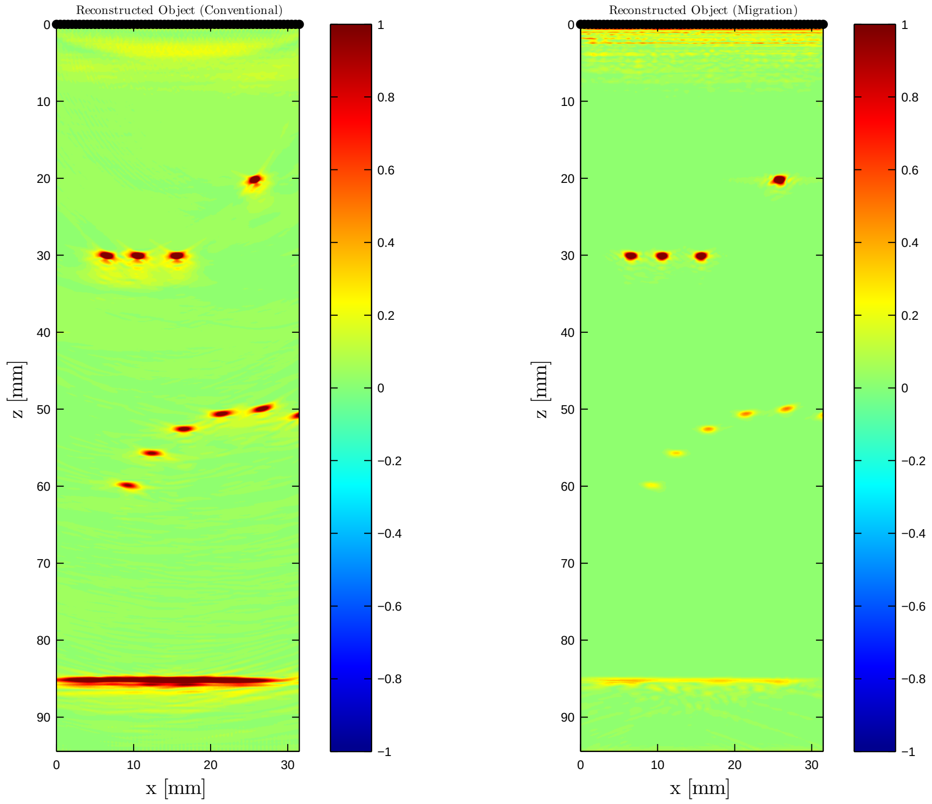

Figure 6: Results of TFM image for the conventional and the migration approaches (multi-static). The element positions are plotted with full black rounds.

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