Development of methods for the analysis of multi-mode TFM images

Sy K$^{1,2,3}$, Bredif P$^2$, Iakovleva E$^2$, Roy O$^1$ and Lesselier D$^3$

$^1$ M2M, 1, rue de Terre Neuve, 91940 Les Ulis, France
$^2$ CEA/LIST/DISC Centre de Saclay 91191 Gif-sur-Yvette cedex, France
$^3$ Laboratoire des Signaux et Systèmes, CNRS-CentraleSupélec-Univ. Paris-Sud, Université Paris Saclay, 3, rue Joliot-Curie, 91192 Gif-sur-Yvette; France

E-mail: kombosse.sy@cea.fr, k.sy@m2m-ndt.com, philippe.bredif@cea.fr, ekaterina.iakovelva@cea.fr, dominique.lesselier@l2s.centralesupelec.fr

Abstract. TFM (Total Focusing Method) is an advanced post-processing imaging algorithm of ultrasonic array data that shows good potential in defect detection and characterization. It can be employed using an infinite number of paths between transducer and focusing point. Depending upon the geometry and the characteristics of the defect in a given part, there are not the same modes that are appropriate for the defect reconstruction. Furthermore, non-physical indications can be observed, prone to misinterpretation. These imaging artifacts are due to the coexistence of several contributions involving several modes of propagation and interactions with possible defects and/or the geometry of the part. Two methods for filtering artifacts and reducing the number of TFM images are developed and illustrated.

1. Introduction

TFM imaging (Total Focusing Method, [1]-[4]) shows a real interest in non-destructive testing since it enables to get an image of the defect facilitating the interpretation of the results. Based on ray tracing, it allows to account for a large number of paths between the transducer and the focusing point: this is the multi-mode TFM imaging ([4][5]).

Depending upon the considered sound path, two kinds of echoes may be observed in the case of a crack: tips diffraction, corresponding to the lower and the upper limits of the crack; and specular echo over the entire length of the defect, which provides an image of the defect. This signature helps to know about the nature of the defect, and thereby eases the inspection. However, the coexistence of several propagation modes yields a large number of images, rendering their analysis difficult, and in addition some indications can be mispositioned within the images, which may lead to further misinterpretation.

This contribution shows how to possibly improve multi-mode TFM images and facilitate their analysis. This paper is organized as follows. In the first section, we recall the principle of multimode TFM imaging. In the second section we illustrate its sensitivity to parameters of interest. Then, in the two last sections, we propose two methods, geometry artifacts filtering and fusion of images, for improving multi-mode TFM imaging.
2. FMC and TFM imaging

Full Matrix Capture (FMC) [6] is a method of data acquisition. It enables to retrieve full transient ultrasonic signals for each transmit and receive element of a linear array probe. For a transducer made of \( N \) elements, it consists in \( N \) successive shots wherein each element transmits a signal and all receive. So a matrix \( S(t) \), the multi-static matrix, of \( N \) by \( N \) elementary signals is obtained, and the TFM post-processing can be applied to it.

The imaging method itself is based on the principle of delay and sum. Focusing is achieved at each point of a pre-defined region of interest, and the amplitude \( I_m(P) \) in each pixel \( P \) for the mode \( m \) is as

\[
I_m(P) = \sum_{i=1}^{N} \sum_{j=1}^{N} S_{ij}(t_{ij}^{P})
\]

wherein \( t_{ij}^{P} \) is the time of flight between transmitter \( i \), receiver \( j \), and focusing point \( P \).

There exists a large number of paths or modes between the transducer and any given point of focusing increased by the coexistence of longitudinal (L) and transverse (T) waves and the possible conversion of waves at the interfaces and on the defect. Three paths or modes are commonly used [7]: direct modes (LL, LT, TL, TT), where the path is without any rebound on the interfaces; corner echo modes (half skip Total Focusing Method) (LLL, LLT, LTL, ...), where the transmitted wave bounces on the bottom before interacting with the defect; and the indirect modes (LLLL, LLLT, LLTL, ...), where the wave bounces on the bottom before and after interacting with the defect.

However, not all such modes are useful. Indeed some provide pertinent information on the defect, yet some just bring artifacts, thereupon rendering difficult the analysis of TFM images. In the next section, the sensitivity of the TFM imaging to some parameters is considered in more detail.

3. Sensitivity of TFM imaging to defect characteristics

TFM images obtained for a given configuration vary depending upon the modes of reconstruction used. Indeed various observations have shown that the TFM imaging is very sensitive to the defect characteristics as well as to the geometry of the part to be inspected.
intend to observe the influence of defect characteristics onto the TFM imaging as a function of the mode used.
In this case, only the corner echo modes, which are allowing specular reflection for the considered defects, are used.

3.1. One defect, several images
A crack of 10 mm height whose end is 5mm from the bottom is retrieved with using 8 corner echo modes, refer to Figure 4.
It shows that the reconstruction of the defect depends upon the mode of reconstruction, as in effect expected. In this example, 3 modes (TTT, TLL, LLT) among the total of 8 considered enable the defect to be retrieved properly, even if this modes are not perfect and present some artifacts. The other modes bring up tips diffraction, and for some, just artifacts. These latter, which look like defects, are penalizing since they indeed increase the risk of misinterpretation from the image observation.

3.2. Influence of defect position
The depth of the defect impacts the TFM reconstruction, that is, for a given mode, the reconstruction depends upon the position of the defect within the structure inspected. To illustrate this phenomenon, two cracks with same height but different positions are imaged with using the TTT mode. The first crack is at 5mm from the bottom and the second crack is at 10mm from the bottom. Each image is normalized in relation to its maximum amplitude.
Figure 3: TFM reconstruction for the crack at 5mm from the bottom (a), at 10mm (b).

The TTT mode enables the first defect to be completely retrieved, refer to Figure 3 (a), while the second one is only partially retrieved, refer to Figure 3 (b). These results show that the position of the defect is indeed crucial for its reconstruction with a given mode.

3.3. Influence of defect orientation
Besides the position, the orientation of a defect impacts the TFM imaging for a given mode. For the same configuration as in the above, two defects orientated at 10° and -10° are retrieved with two modes, the TLT and TTT ones.

The TTT mode which is appropriate for the defect orientated at 10°, refer to Figure 4(a), becomes inappropriate for the defect with the opposite orientation, refer to Figure 4(c), contrary to the TLT mode, refer to Figures 4(b) and 4(d). The choice of the pertinent mode thus becomes complicated when the orientation of the defect is unknown.
To conclude, the TFM imaging is very sensitive to the defect characteristics, and not just elsewhere. Indeed the specular reflection allowing the defect imaging is a geometrical phenomenon. So, for a couple of transmitter and receiver, the physical path is a path that obeys the Snell law on the interfaces, and also on the defect. This path is sensitive to the profile of the interfaces, the velocities of the considered waves, the orientation and the position of the defect, and even the relative position between the defect and the transducer.

Without any hypothesis on the defect, several reconstructions with several modes are needed to increase the likelihood of getting the pertinent modes, which greatly increase the number of images to analyze, which come with their own set of artefacts. The analysis mode by mode could be tedious, a method for analysing simultaneously all images is proposed next. But, before to do that the origins of artefacts are explained and a method to filter those due to the geometry echo is proposed.

4. Artefacts: origins and filtering
As shown in the preceding section, artifacts may appear in TFM imaging, being emphasized that we call artifacts all coherent indications present in the image but not corresponding to an actual defect. These artifacts, due to the coexistence of several modes in the same received signal, are derived from the defect echo or the geometry echo. In some cases they look like a defect and improve the risk of misinterpretation, and in others their amplitude is so strong that they can hide the defect indication.

4.1. Non-uniqueness of time of flight in the same mode
As described, the times of flight are not unique in TFM imaging. Indeed, in the same mode, we have isochronous curves which are ellipses of which all points are associated to the same amplitude. If a defect is present at a point, the summation of amplitudes of all couples is coherent and the TFM amplitude increases. Otherwise, it vanishes.

But in some configurations, where the elements of the phased array are not ‘enough’ divergent, or if the defect length is very large vs. the transducer aperture, the interferences are not sufficient to completely cancel the amplitude outside the defect location, so the quality of images is
deteriorated. The removal of these artifacts involve the optimization of the inspection and is not discussed in this statement.

4.2. Non-uniqueness of time of flight in different modes

It is also possible to have the same time of flight and so the same contribution for two different modes. In this case, an indication at a given location, for a given mode, will be positioned at another location, for another mode. When the artifacts is due to the defect, we observe some echoes looking like a defect, seen in the section 2.1, and when it is due a specular geometry echo, we can have in some cases, especially in corner echo modes, an artefact with a very high amplitude. To filter it, we apply one method [8] based on the notion of specular path at the focusing point. Its principle is to attenuate all path without specular meaning by introducing a modification in the TFM algorithm. This method has been applied on experimental data. Two images before and after filtering are presented for LLL mode (cf. Figure 5).

![Figure 5: TFM reconstruction for LLL mode (a) without geometry artifacts filtering, (b) with geometry artifacts filtering](image)

The artefact is completely removed by this method, refer to Figure 5(b), noticing however that the artifacts due to the defect echo are not removed by this filtering. In addition, let us specify that this algorithm works well if and only if, the geometry echo is separable from the defect echo.

Once the images filtered from geometry artifacts, several combinations of modes are possible to analyze more easily images. Combinations must be done as to do not lose information about the defect, and wherever possible, to reduce artifacts.

5. Fusion of modes by summation

It has been shown in the second section that multi-mode TFM imaging yields a large number of images which can be tedious to analyze, and in addition the pertinent information can come from several modes. So fusion of modes is a mean to simultaneously exploit all information and it can be carried out so as to filter or at least to reduce artifacts due the defect (observed in Figure 2). The fusion is performed for all modes having the same type of paths, which means the
4 direct modes between them, the 8 corner echo modes between them and the 16 indirect modes between them. So the number of images goes from 28 to 3, greatly facilitating the analysis. In this contribution the examples presented are for corner echo modes.

The summation of modes is a simple mean to not lose any information by exploiting the complementarity of modes. The final amplitude $I_{sum}$ is such that

$$I_{sum}(P) = \sum_{m=1}^{M} |I^m(P)|$$

(2)

where $M$ is the number of modes to take into account. The summation of the absolute value of images is explained by the fact that the modes have not the same phase, so they can cancel themselves on the defect by summation; however the summation of the absolute values deteriorates the SNR since the noise for all modes is added up constructively.

To illustrate the said method, the 8 images of Figure 2 are added up according to the relation (2). The defect is correctly retrieved, refer to Figure 6, and there is no loss of information.

Figure 6: Fusion by summation of the 8 corner echo modes of Figure 4.

The defect is correctly retrieved, refer to Figure 6, and there is no loss of information. However, the summation brings also artifacts of all modes that are intervening in the fusion. These artifacts can be reduced if a preselection of modes is made before the summation. Indeed in this example, the most energetic artifacts come from the modes LLL and LTL (Figure 4 (a and c)), where these modes have a low refraction coefficient on the interfaces for the used transducer which mainly transmits transverse waves at 45°.

Simply adding modes with transverse waves at refraction, which are TLL, TLT, TTL and TTT, the most energetic, we observe, refer to Figure 7, that the artifacts are much reduced and the defect is properly reconstructed. In addition, the reduction of the number of modes allows to improve the SNR.
6. Conclusion
In this contribution, we illustrate some limits of TFM imaging, particularly its sensitivity to the defect characteristics and the reconstruction artifacts. The proposed method of artifacts filtering then applied onto experimental data shows a good capability to filter geometry artifacts. The method of fusion by summation which is proposed for exploiting simultaneously all modes presents the advantage not to lose defect indication, but it should be accompanied by methods of artifacts filtering. The preselection of modes showed a considerable reduction of artifacts, however, the energetic criterion is not sufficient to predict pertinent modes. Indeed, the specular echo also is a geometric phenomenon, the hypothesis of the knowledge of the defect orientation could permit a prediction of pertinent modes, and thus a best preselection of modes.

7. Works in progress
In the next work, a method for predicting relevant modes will be developed. This method allows to reduce considerably the artifacts and the modes to take into account for the defect reconstruction.

The method is based in the research of specular paths on the defect, requiring the knowledge of the defect orientation. It allows to predict a zone, called coverage area, in the defined region of interest, where a defect can be reconstructed. Once the coverage area is determined for a several modes, modes will be selectionned based on some criteria (maximal amplitude, maximal coverage, ...). In the case where several modes are necessary to reconstruct the defect, other methods of fusion will be proposed.

8. References
[1] Karaman M, Pai-Chi L and O'Donnell M 1995 Synthetic aperture imaging for small scale systems, *IEEE Trans. Ultrason., Ferroelec, Freq. Control* **42** 429-42
[2] Holmes C, Drinkwater B W and Wilcox P. D 2005 Post-processing of the full matrix of ultrasonic transmit-receive array data for non-destructive evaluation, *NDT & E Intern.* 38 701-11

[3] Bannouf S, Robert S, Casula O and Prada C 2013 Data set reduction for ultrasonic TFM imaging using the effective aperture approach and virtual sources *J. Phys.: Conf. Series* 457 012007

[4] Le Jeune L, Robert S, Lopez Villaverde E and Prada C 2016 Plane wave imaging for ultrasonic non-destructive testing: Generalization to multimodal imaging, *Ultrason.* 64 128-38

[5] Zhang J, Drinkwater B W, Wilcox P.D and Hunter A. J 2010, Defect detection using ultrasonic arrays: The multi-mode total focusing method, *NDT & E Intern.* 43 123-33

[6] Sutcliffe M, Weston M, Dutton B, Charlton P and Donne K 2012 Real-time full matrix capture for ultrasonic non-destructive testing with acceleration of post-processing through graphic hardware, *NDT & E Intern.* 51 16-23

[7] Felice M V, Velichko A and P D. Wilcox 2014 Accurate depth measurement of small surface-breaking cracks using an ultrasonic array post-processing technique, *NDT & E Intern.* 68 105-12

[8] Iakovleva E, Chatillon S, Bredif P and Mahaut S 2014 Multi-mode TFM imaging with artifacts filtering using CIVA UT forwards models, *AIP Conf. Proc.* 1581 72