Multi-mode TFM imaging with artifacts filtering using CIVA UT forwards models

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Ekaterina Iakovleva[a], Sylvain Chatillon[a], Philippe Bredif[a], Steve Mahaut[a]

[a]*CEA, LIST, DISC, F-91191, Gif-sur-Yvette cedex France*

Abstract. TFM (Total Focusing Method) is an advanced post-processing imaging algorithm of ultrasonic array data that shows great potential in defect detection and characterization. This technique can be performed using several propagation modes (direct or over skip imaging) and several types of waves (longitudinal or transverse) allowing the imaging of extended defects of complex geometry. However, non physical indications can be observed, leading to misinterpretation. These imaging artifacts are due to the coexistence of several contributions involving several mode of propagation and interactions with possible defects and / or the geometry of the part. In several configurations, a simple time of flight criterion is not sufficient for their identification. This paper presents tools based on the forward CIVA UT models which allow to analyze and to filter these artifacts, without any tuning parameters. The performances achieved are compared to those of conventional TFM on simulated and experimental data.

Keywords: Phased Arrays, UT Inspection, Imaging, Simulation, TFM, Artifacts, Filtering
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INTRODUCTION

TFM (Total Focusing Method) is an advanced post-processing imaging algorithm of ultrasonic array data that shows great potential in defect detection and characterization. This technique can be performed using several propagation modes (direct or over skip imaging) and several types of waves (longitudinal or transverse) allowing the imaging of extended defects of complex geometry [1,2,3,4]. Additionally, the TFM methodology allows data visualization in both two and three dimensions [5]. This imaging technique is implemented in the CIVA software and offers three commonly used imaging modes: direct, corner echo and indirect imaging [5,6]. The use of several imaging modes allows to get complementary information related to the defect (images of edges related to tip diffraction echoes in direct mode, profile of a crack-like defect in specular or corner echo modes) as shown on the next application examples.

However, in addition to the desired echoes from the defects, the TFM images may contain non-physical indications, also called image artifacts. The most commonly encountered artifacts in TFM imaging are due to the coexistence of several contributions involving several mode of propagation and interactions with possible defects and/or the geometry of the part. These image artifacts are problematic since they create false information that may be a source of confusion and erroneous interpretation. To ensure the full exploitation of various imaging modes it is necessary to recognize and, if it is possible, to filter these artifacts to provide a correct interpretation of TFM images.

This paper presents new methods based on the forward CIVA UT models which allow to analyze and to filter image artifacts. The first method, also called Echo Transformation Method (ETM), has been developed for the analysis of indications present in TFM images. This method allows predicting the artifacts associated with physical indications, such as defect and geometry echoes, in different TFM imaging modes by applying a simple time of flight criterion. This approach can also be used as a filter designed to remove these artifacts from the TFM images. Two other filtering methods, known as parametric and weighting filters, have been developed especially for filtering of imaging artifacts induced by backwall echo from the corner echoes TFM reconstructions. These filtering processes are performed by applying an angle criterion. The performances achieved by the new methods are also presented and compared to those of conventional TFM on simulated and experimental data.

This paper is organized as follows. The first part recalls the principle of the multi-mode TFM imaging. The second part describes the mechanism behind the production of image artifacts. The new methods allowing their recognition and in some cases, their filtering, are presented in the third part of this document.

MULTI-MODE TFM IMAGING

The TFM imaging is a technique used to post-process the data from Full Matrix Capture (FMC) [1,3]. For an ultrasonic array of N elements, the FMC acquisition consists in recording a set of NxN elementary signals $S_{ij}(t)$, where (i, j) is a transmit and receive element combination, $1 \leq i,j \leq N$. The post-processing algorithm consists then in coherent summation of all acquired data in order to focus the array at every point in a given Region Of Interest (ROI), so that an image of this region can be produced. Mathematically this can be expressed as:

$$I(P) = \sum_{i,j=1}^{N} S_{ij}\left[t_{ij}(P)\right] \tag{1}$$

where $t_{ij}(P)$ denotes the theoretical time of flight corresponding to the propagation time between the i-th transmitter and the j-th receiver, through the point P.

The TFM imaging can be performed using several propagation modes (direct or over skip imaging) and several types of waves (longitudinal or transverse). For over skip imaging, the theoretical times of flight in (1) include ray paths with one or more reflections at the backwall, while for direct imaging, the considered ray paths do not contain any backwall reflection. This TFM imaging is implemented in the CIVA software and offers three commonly used imaging modes shown in Figure 1: direct, corner echo and indirect imaging.

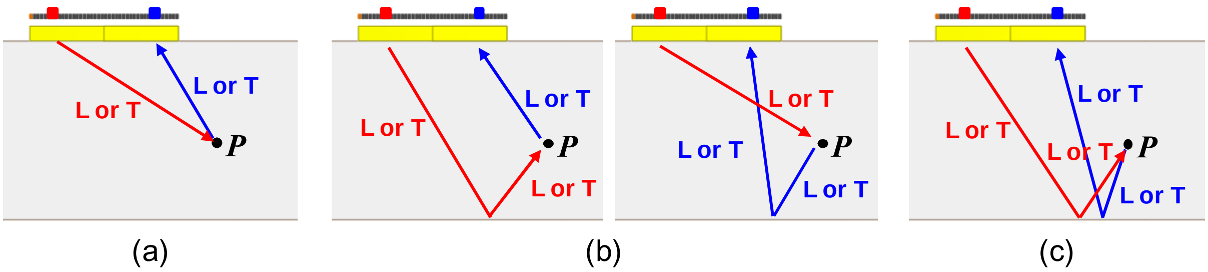

FIGURE 1. Scheme of the different TFM imaging modes: a) direct imaging, b) corner echo imaging, c) indirect imaging.

In this paper the following notation is used for direct, corner echo and indirect TFM imaging. The letters L and T represent longitudinal and transverse waves, respectively. For direct TFM, the first letter corresponds to the path between the transmitter and the image point, the second letter corresponds to the path between the image point and the receiver. For corner echo TFM, the first letter corresponds to the path between the transmitter and the backwall, the second, the path between the backwall and the image point, and the third letter, the path between the image point and the receiver. For indirect TFM, the first letter corresponds to the path between the transmitter and the backwall, the second, the path between the backwall and the image point, the third letter, the path between the image point and the backall, and the fourth letter, the path between the backwall and the receiver.

Figure 2 shows an example of direct and corner echo TFM imaging from simulated data using CIVA software. The FMC simulation has been performed in contact mode on a steel planar block containing a vertical breaking notch of 10 mm height. The 2-MHz ultrasound array transducer consists in 42 elements. Figure 2(a) and (b) show the results for the direct TT and corner echo TTT modes, respectively. In both cases, the simulated data is post-processed using Equation (1) in which the theoretical times of flight are calculated considering waves with a transverse polarization. These results show that the multi-mode TFM provide complementary indications of the defects and therefore, the combined use of different imaging modes offers a great potential for defect characterization in terms of size, nature and orientation. Indeed, in the case of the direct TT mode, the notch is imaged as two tip diffractions, while for the corner echo TTT mode, the notch is imaged along its entire length showing its flat nature. Two tip diffractions and corner echo then can be used to estimate the defect height and its orientation, respectively.

Figure 3 shows an example of corner echo and indirect TFM imaging from simulated data. The inspection setup is identical to that used in Figure 2. The steel planar block contains a 45° tilted breaking notch of 10 mm height. Figure 3(a) and (b) show the results for the corner echo TTT and indirect TTTT modes, respectively. In comparison with previous example, the 45° tilted breaking notch is imaged now as two tip diffractions in corner echo TTT mode. For the indirect TTTT mode, the notch is imaged along its entire length. In this case, the defect height and its orientation can be estimated using two tip diffractions and indirect echo, respectively.

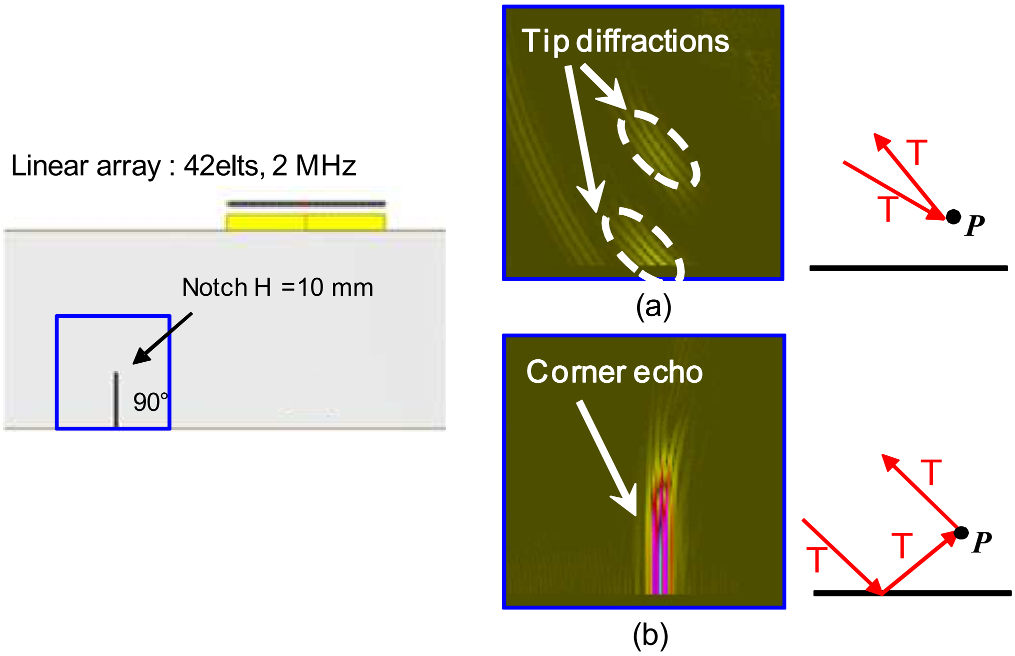

FIGURE 2. Imaging of a vertical breaking notch in a steel block: a) direct TT imaging, b) corner echo TTT imaging.

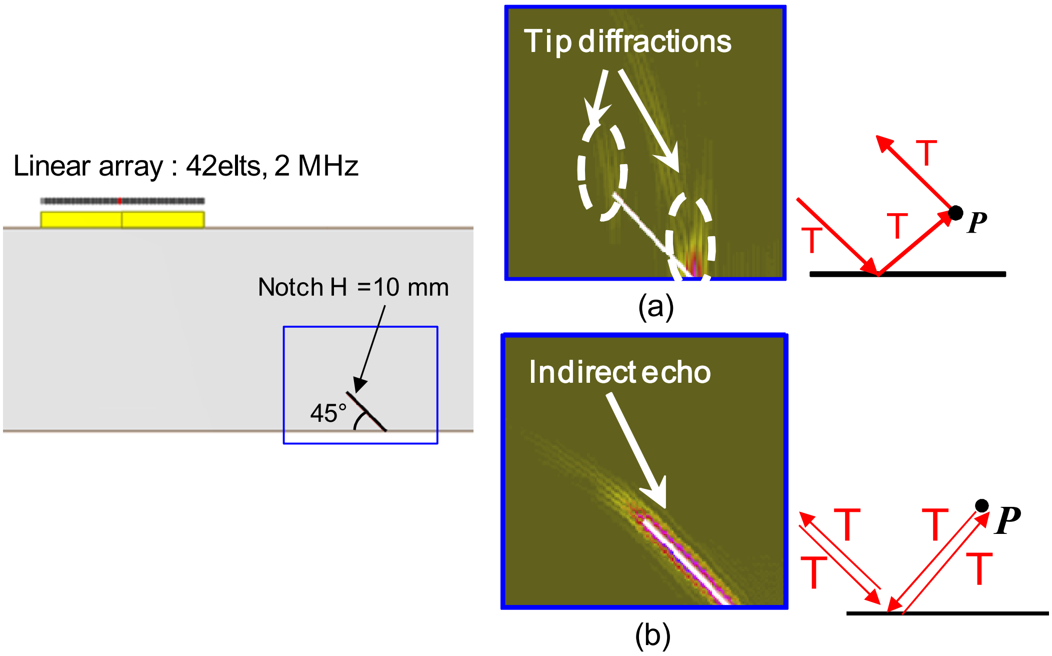

FIGURE 3. Imaging of a 45° tilted breaking notch in a steel block: a) corner echo TTT imaging, b) indirect TTTT imaging.

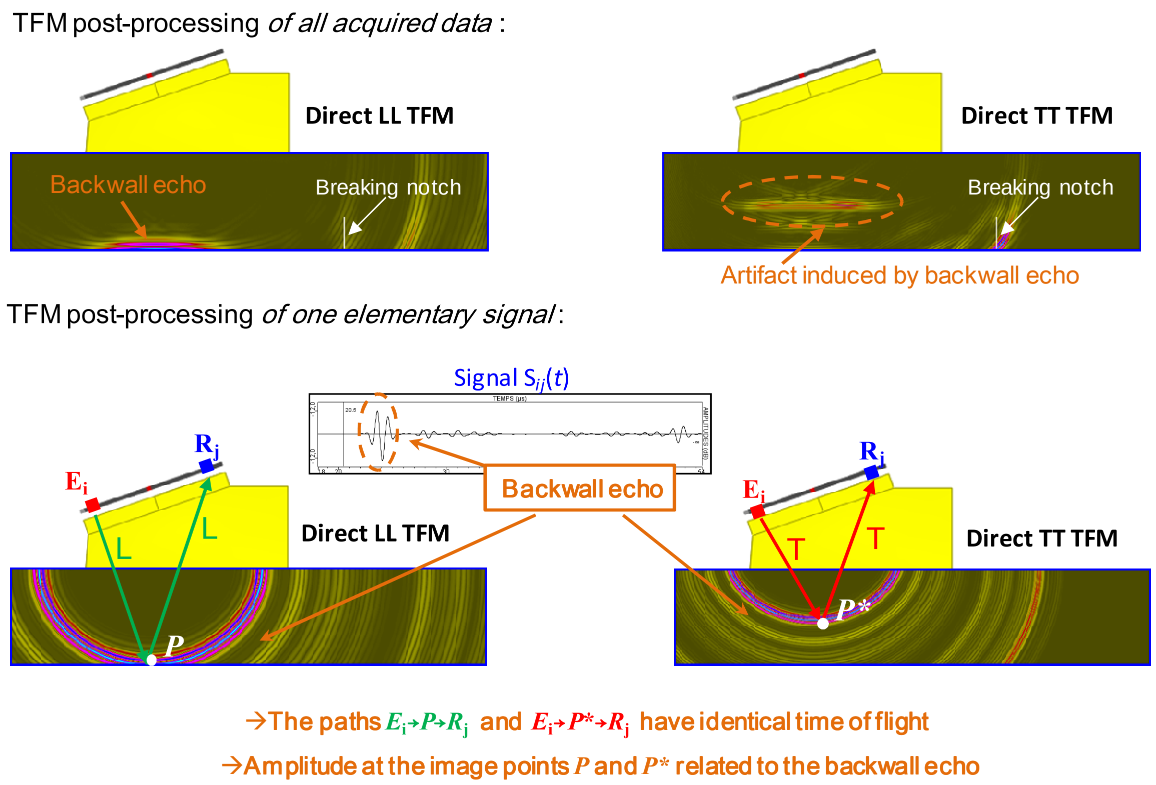

FIGURE 4. Illustration of the non uniqueness of time of flight between different ultrasound paths possible and different TFM imaging modes.

IMAGE ARTIFACTS

A large number of multi-mode TFM reconstructions performed on simple and complex geometries have shown that the defect and geometry echoes detected in some reconstruction mode may induce non-physical indications in other reconstruction modes. These indications are called image artifacts and are generally due to the vicinity of time of flight of different contributions, corresponding to different ultrasound paths. The mechanism behind their production is illustrated in Figure 4 by an example of an artifact induced by backwall echo in direct TT TFM imaging mode. In this example, the FMC simulation has been performed in contact with 1-MHz ultrasound wedge transducer of 32 elements on a steel planar block containing a vertical breaking notch of 10 mm height. It can be seen, that in the case of the direct LL TFM imaging, the backwall echo is correctly positioned in the inspected component. For the direct TT TFM image we observe high amplitude artifact located below the transducer. This is due to the vicinity in time of arrival of the LL backwall reflection and the time needed for a transverse wave to propagate between transmitters and receivers through image points located in the image area containing artifact.

This example shows that image artifacts create false information that may be a source of confusion and erroneous interpretation. To ensure the correct interpretation of TFM reconstructions, it is necessary to recognize and, if possible, to filter these artifacts.

ANALYSIS TOOLS AND FILTERING OF IMAGE ARTIFACTS

This section describes the new methods allowing to analyze and in some cases, to filter the image artifacts. These methods are very simple in their implementation and can be applied to both two and three dimensions multi-mode TFM imaging. The first method is called Echo Transformation Method (ETM). This method allows recognition and filtering of image artifact induced by physical indications as defect and geometry echoes. Two second filtering methods presented here, also called parametric and weighting filters, are designed to reduce image artifacts caused by geometry echoes in corner echo TFM imaging modes. These filtering techniques do not require prior identification of image artifacts.

Echo Transformation Method

Echo Transformation Method (ETM) has been developed for the analysis of indications present in TFM images. This method can be applied to different physical indications, such as defect and backwall echoes, detected in some given TFM mode to predict the artifacts associated with these indications in other imaging modes. The ETM method can also be used as a filter designed to remove image artifacts. The principle of the ETM is summarized in the following steps:

Step 1: For a TFM image obtained with one imaging mode, selection of an area denoted ROI, containing an echo whose origin is identified.

Step 2: Extraction of time of flight data associated with each point of ROI.

Step 3 (analysis): TFM post-processing with another imaging TFM mode only using the time of flight data selected in step 2.

Step 4 (filtering): TFM post-processing with another imaging TFM mode without using the time of flight data selected in step 2.

The principal steps of transformation are illustrated in the Figure 5. The inspection setup is identical to that used in Figure 4.

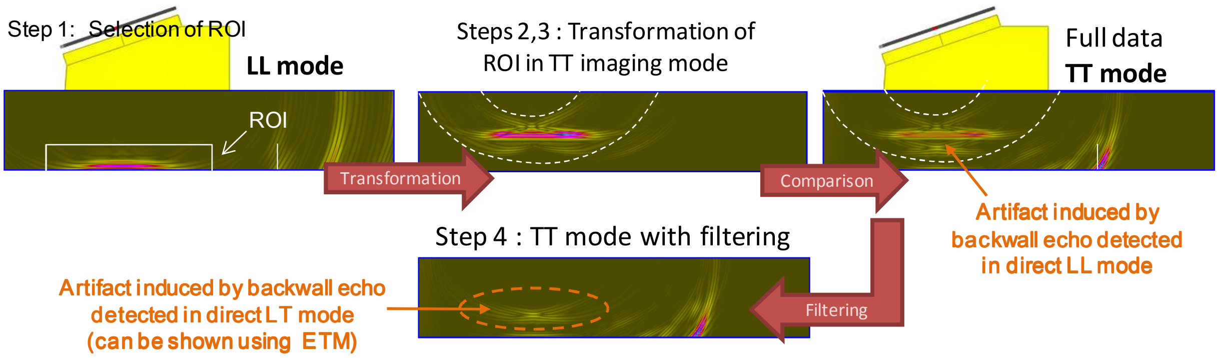

FIGURE 5. Illustration of the principal steps of EMT algorithm.

From the first three steps of the above algorithm, it follows that the ROI selected in step 1 and the TFM image obtained in step 3 of the algorithm contain the indications of the same origin. In the example shown in Figure 5, it is possible to deduce that the backwall echo detected in direct LL TFM image induces the artifact surrounded by dotted lines in direct TT TFM image. The result of the filtering of this artifact is also given in Figure 5. Using the same procedure, it can be shown that the image artifact surrounded by dotted line in the filtered TT TFM image is induced by the backwall echo detected in direct LT TFM mode. Thus, the consecutive application of ETM allows to interpret the nature of a large number of indications in TFM images.

Filtering of Artifacts in Corner Echo TFM

A large number of TFM reconstructions have shown that the backwall reflection may generate high amplitude artifacts in corner echo TFM mode. These artifacts are due to non-physical ultrasonic paths used in corner echo TFM post-processing. Indeed, as shown in Figure 6, the paths for which the angle between the forward (transmitter to image point) and the backward (image point to receiver) directions close to 180 ° cannot exist in corner echo mode reconstruction carried out over a planar crack, or over a large volumetric flaw. Therefore, filtering of image artifacts induced by the backwall reflection in corner echo TFM imaging mode can be reduced to filtering of ultrasonic paths without physical meaning. This filtering can be performed by applying an angle criterion.

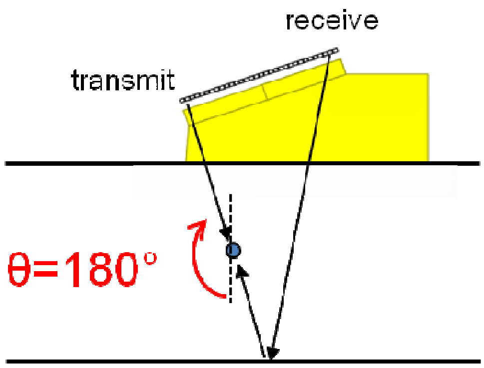

FIGURE 6. Corner echo reconstruction without physical meaning.

The first filter described here, also called parametric filter because of its dependence on the parameter, removes the paths for which the angle, θ, between the forward and the backward directions is greater than $\hat{\theta}$, where $\hat{\theta}$ is an arbitrary value close to 180°. Disadvantage of this approach is its dependence on the setting of $\hat{\theta}$ that may result in elimination of useful paths.

The second filter which is called weighting filter, allows to control the angle θ by introducing a weighting function as:

$$f(\theta) = cos^2(\theta/2) = (1 + cos\,\theta)/2 \tag{2}$$

It can be seen that the weight function *f* takes the values close to 0 for angle θ close to 180 °. This function is then integrated in the equation (1) as follows:

$$I(P) = \sum_{i=1}^{M}\sum_{j=1}^{N} f_{ij}(P) \cdot S_{ij}(t = T_{ij}(P)) \tag{3}$$

where $f_{ij}(P) = f(\theta_{ij}(P))$ and $\theta_{ij}(P)$ denote the angle between the forward and the backward directions at the image point *P* for the *i*-th transmitter and the *j*-th receiver. In the above equation, the weight function *f* is designed to remove non-physical ultrasonic paths.

Figure 7 shows an example of application of parametric and weighting filters on a planar component. The inspection setup is identical to that used in Figure 4. In the case of parametric filter, the results are presented for two different parameters $\hat{\theta}$: 130° and 120° (Figs. 7a and 7b). The result of application of weighting filter is illustrated in Figure 7c. This example shows the advantage of using the weighting filter relative to the parametric filter. It can be seen that the artifact induced by the backwall reflection is completely removed from the corner echo TFM image by parametric filter for $\hat{\theta}$= 120°, while for the first parameter this artifact is still present in the image. In the case of the weighting filter, this artifact is removed at once, without affecting the reconstruction of the notch.

The weighting filter has been applied on complex geometries. An example of this application using simulated data is shown in the Figure 8. The FMC simulation has been performed in immersion on a homogeneous stainless steel mock-up. The mock-up contains a flaw which consists in a 20° tilted breaking notch of 3 mm height located near the bead weld. The 2-MHz ultrasound array transducer consists in 24 elements. The results show that for weighting filter the artifact is completely removed from the corner echo TTT TFM image without affecting the reconstruction of the notch.

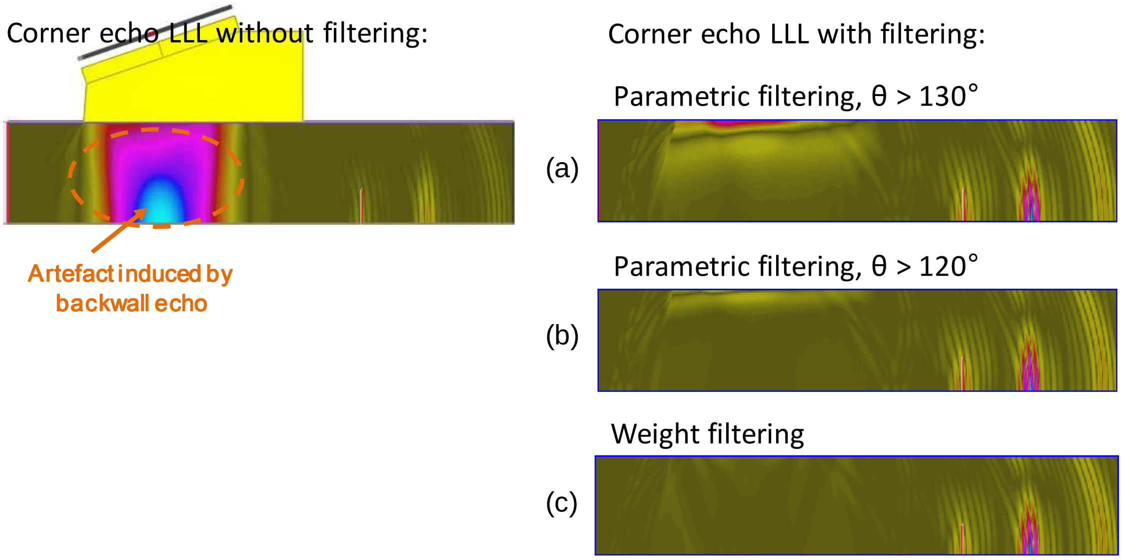

FIGURE 7. Example of application of parametric and weighting filters on a planar component: a) parametric filtering for $\hat{\theta}$= 130°, b) parametric filtering for $\hat{\theta}$= 120°, c) weight filtering.

Figure 9 shows an example of application of weighting filter using experimental data. The FMC acquisition has been performed in contact mode with 2-MHz ultrasound array transducer of 42 elements. The inspected component is made of homogeneous stainless steel and contains a 20° tilted breaking notch of 3.5 mm height. Figure 8(a) shows the results for corner echo TTT and TTL TFM modes which contain high amplitude artifacts induced by the backwall reflection. Figure 9(b) shows the results of application of weighting filter for both corner echo imaging modes. Once again the results show that the image artifacts are completely removed from the corner echo imaging modes.

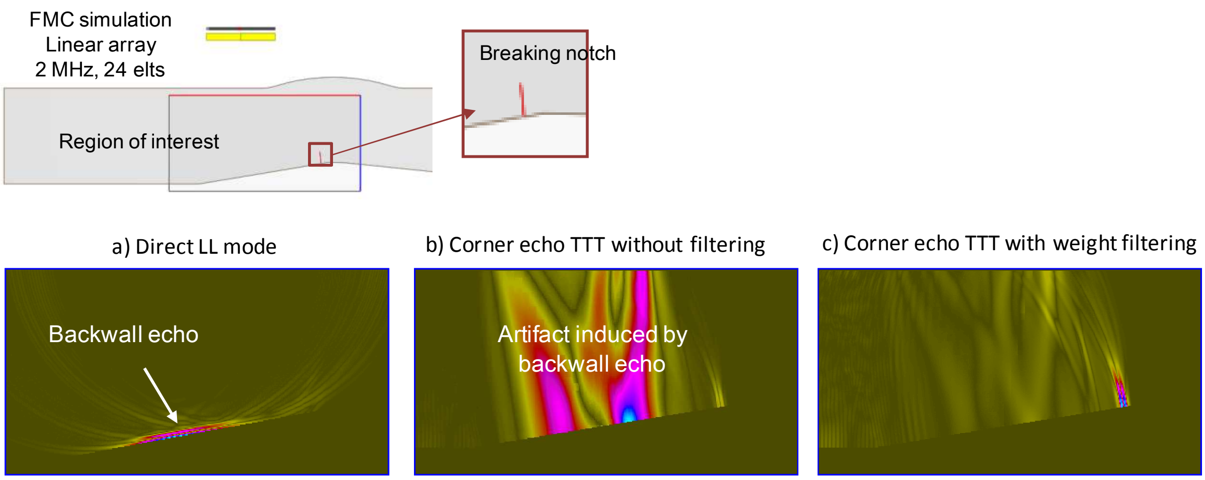

FIGURE 8. Example of application of weighting filters on a complex geometry using simulated data: a) direct LL imaging, b) corner echo TTT imaging without filtering, c) corner echo TTT imaging with weight filtering.

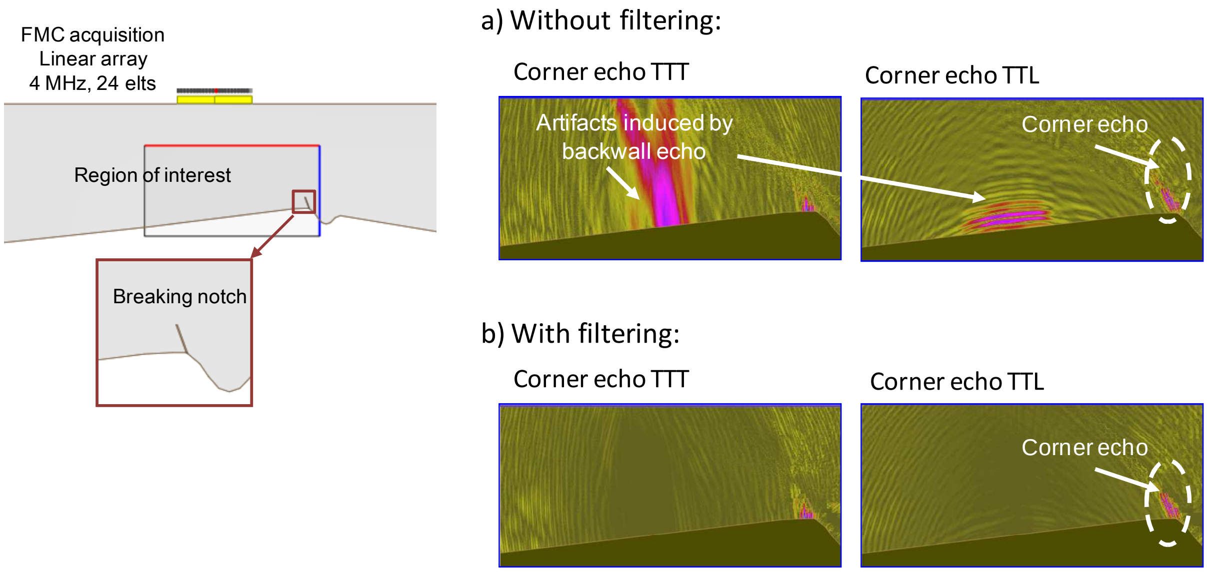

FIGURE 9. Example of application of weighting filters on a complex geometry using experimental data: a) corner echo TTT(left) and TTL(right) imaging, b) corner echo TTT(left) and TTL(right) imaging with weight filtering.

CONCLUSION

In this paper, new techniques to analyze and to filter the image artifacts in multi-mode TFM were presented. The Echo Transformation Method allows recognition and filtering of image artifact induced by physical indications as defect and geometry echoes. New filtering techniques (parametric and weighting filters) to improve the quality of corner echo TFM imaging were also presented. These methods are designed to reduce image artifacts caused by geometry echoes in corner echo reconstructions and do not require their prior identification. They are based on control of angle formed by forward and backward directions at each image point. Results obtained on simulated and experimental data have shown the effectiveness of the weighting filter for corner echo TFM imaging. They have shown a significant reduction in the number of artifacts on TFM images, with the advantage of not having to enter settings, and that the weighting filter does not affect the reconstructions of the defects. All described methods are very simple in their implementation and can be applied to both two and three dimensions multi-mode TFM imaging.

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