Feasibility study of the characterization of planar defects in a circular weld with TFM

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Abstract

This paper reports results from a feasibility study carried out by EXTENDE and EDF CEIDRE about characterization of planar defects located in a welded cylindrical specimen with the Total Focusing Method (TFM). First, the characterization of EDM notches in a welded part with a complex internal profile is evaluated by simulation. The simulated results are compared to experimental ones and show good agreement. A characterization procedure for planar defects with TFM is proposed. It is applied to fatigue cracks and shows convincing results. Detection but also characterization of planar breaking backwall defects seem possible with TFM when using LL direct mode reconstruction of the region of interest. However, corner echo mode reconstruction may also complete and confirm the defect characterization depending on some conditions detailed in this paper (probe positioning, geometry knowledge, …).

1. Introduction

The French regulations require EDF to qualify before on-site implementation all Non-Destructive Examinations carried out on the Main Primary and Secondary circuits of PWR plants. The qualification process consists in a demonstration of the capability of an NDE to ensure that the performance meets the requirement from safety. In this demonstration, geometries of welded assemblies to be inspected are taken into account when determining the NDE performance. When detecting an indication, artifact/defect discrimination and even defect sizing must be carried out; each situation is most often dealt with on a case-by-case basis. Some geometries with limited access for probes on one side of the weld can lead to area coverage or characterization limitations.

To deal with these situations in a more generic way, EDF CEIDRE wishes to investigate the interest of the Total Focusing Method (TFM) to allow artifact/defect discrimination and defect sizing in these configurations. TFM imaging is an imaging technique implemented in CIVA simulation and analysis software and in some acquisition systems. EXTENDE performed an experimental and simulation study; the aim was to evaluate the ability of the TFM technique and its performances to assess the potential for artifact/defect discrimination and sizing of thermal fatigue cracks in circular welds with limited access. One of the key point is to use indirect TFM modes that may be difficult to reconstruct correctly because of the complex internal profile.

2. Experimental set-up

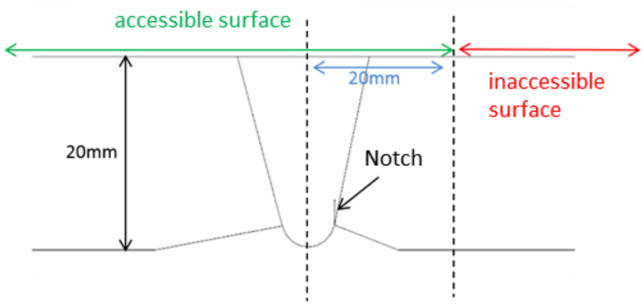
2.1 Specimens

The specimen used to evaluate the performance of the TFM method is a cylindrical specimen of 10mm width made of ferritic steel and which material properties are:

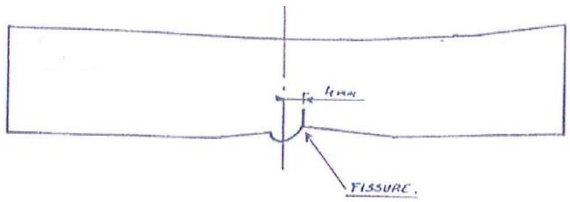
- Longitudinal wave velocity: 5900 m / s
- Shear wave velocity: 3230 m / s
- Density: 7.8 g / cm3

This specimen includes several EDM notches from 1.5 mm and 8 mm high along the slopes. A sketch of the circular weld is presented on Figure 1(a). It shows the accessibility limitations to be considered during control: the zone located 20mm beyond the centre of the weld on the side's flaw cannot be used for inspection.

Experimental validations were also carried out on small cuts of a component of the same diameter. They all present a real thermal fatigue crack. These specimens are characterized by a twisted surface and a complex backwall. The weld bead is very irregular; its depth changes along the extrusion of the component. Therefore, the geometry of the cuts is 3D. Figure1(b) and (c) show the actual profile of the cuts as well as the position of the crack.



(a)



(b) Sketch of a cut (c) Photograph of a cut

Figure 1: Studied specimens

2.1. Probe and acquisition system

A 5 MHz phased-array probe of 64 elements (pitch 0.6mm) was used for the control. Its characteristics (aperture, frequency, pitch) were chosen according to the access restrictions on the specimen, the component thickness, the dimensions of the target defects and the divergence of the transmitted beam.

This probe has been used with a M2M MultiX acquisition system for its ability to save an FMC acquisition. The post-processing of the FMC is necessary to reconstruct the TFM image in corner echo mode using a complex 2D CAD profile since the current portable acquisition systems integrating real-time TFM imaging do not yet allow such reconstructions.

2.3 The Total Focusing Method

A FMC acquisition corresponds to a fixed array position acquisition of the full inter-element matrix $\mathbf{K}(t)$. For an array of N active elements, it is constituted by the $N \times N$ stored impulse inter-element responses $k_{ij}(t)$ defined as the output of the element number j when the input of the element number i is a delta impulse. TFM is a synthetic imaging algorithm implemented in CIVA which post-processes the full inter-element matrix $\mathbf{K}(t)$ and provides a high-resolution image of a Region Of Interest (ROI). Its principle is to coherently sum all elementary signals $k_{ij}(t)$ of $\mathbf{K}(t)$ in order to focus, *a posteriori*, in every point of the ROI. The amplitude A at the point M in the image is given by (1, 2):

$$A(M) = \sum_{i,j} k_{ij}\left(T_{ij}^{M}\right) \quad (1)$$

where T_{ij}^{M} is the theoretical time of flight between M and a pair of elements (*ij)*.
The calculation of the time of flight according to the procedure described above is specific to the so-called “direct” reconstruction mode. Other modes of reconstruction can be used in TFM imaging as the so-called “indirect” mode and the “corner echo” mode. These imaging modes are available in the CIVA software and consider multiple ultrasound paths and possible mode conversions when flaws are located near an interface of the inspected part.

3. Results

3.1 Characterization with TFM in direct mode imaging

TFM imaging in direct mode leads to "classic" images of a defect. The reconstructed echoes look like those that can be observed on a Bscan resulting from a sector scan, electronic scanning... With these kinds of images, one method to discriminate artifact from flaw rely on changing the probe position. According to the probe positioning, there are 2 ways to characterize a breaking backwall notch. Thus, according to the position of the probe relatively to the defect, a breaking backwall planar defect could be characterized by either both top and bottom diffraction echoes, either by the top diffraction echo and a break in the continuity of the backwall echo.
Figure 2 shows the TFM images of a 3mm height notch resulting from experimental and simulation data for 2 probe positions. Results show a very good agreement between CIVA simulation and experiment. For both cases, the expected echoes are well imaged.
Measuring the distance between the top diffraction echo and the bottom one or the break in the backwall continuity leads to an accurate evaluation of the notch height. The error on this measurement is ± 0.2mm and is linked to the reconstruction grid resolution.

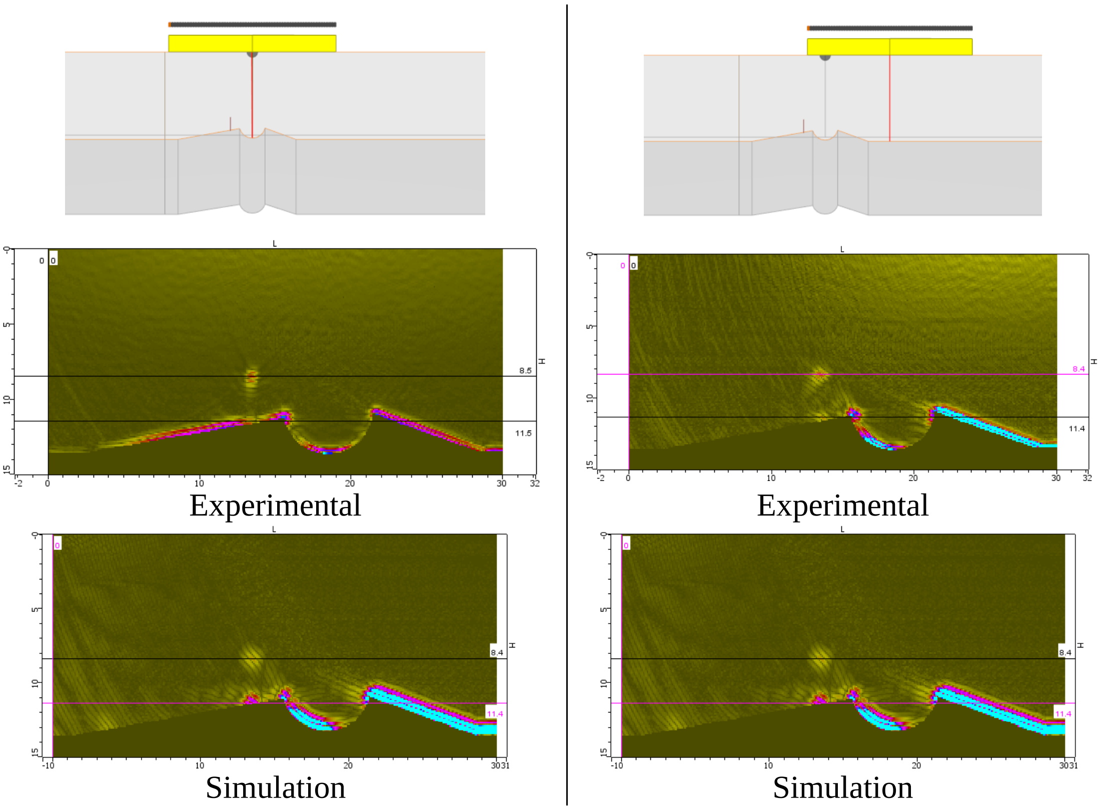
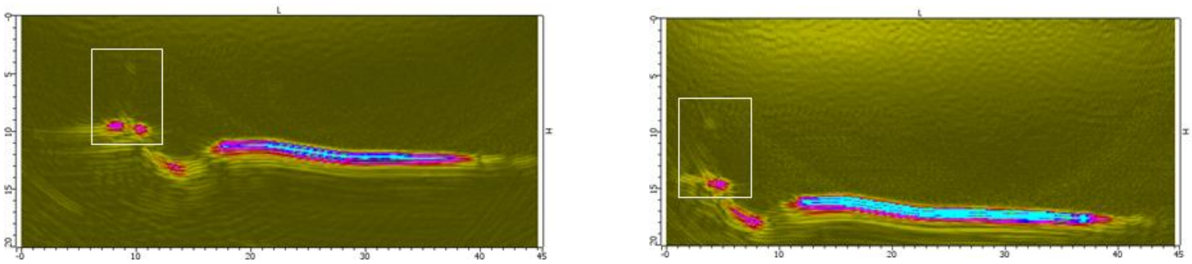


Figure 2 : Experimental and simulated TFM images of a 3mm high notch for 2 positions of the probe. Images at left: probe aperture covering the weld and notch. Images at right: notch outside the probe aperture

The characterization performance of TFM imaging has also been evaluated on a 3 mm high fatigue crack type defect. TFM images in LL mode of a fatigue crack are shown in Figure 3. Figure 3(a) is associated with the configuration where the probe aperture is above the crack, Figure 3(b) is associated with the shifted probe configuration. When the crack is located below the probe aperture, the flaw is characterized by a poor diffraction echo and a break in the backwall echo. When the crack is located outside the probe aperture, it is characterized by two echoes, one at the top and one at the bottom of the flaw.

The difference in height between the top diffraction echo and the bottom one or the break in the backwall echo corresponds to the crack height. The measured height is equal to the theoretical height of the defect ± 0.2mm. This has been checked on several specimens and cracks.



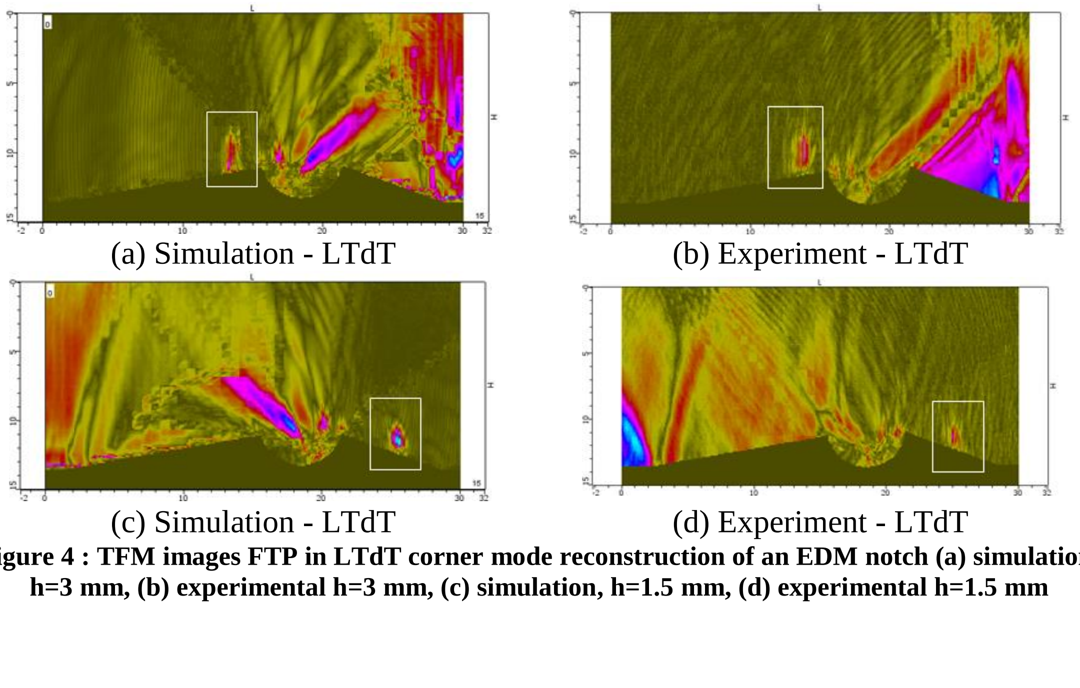
(a) (b)

Figure 3 : TFM images in LL direct mode of a thermal fatigue crack

These results show that characterization of a breaking backwall defect (EDM notch and real fatigue crack) is possible with TFM in LL mode. These results are available provided that the noise level is sufficiently low.

3.2 Characterization with TFM in corner echo mode imaging

In unfavourable conditions (strong structural noise level), LL direct mode may not be sufficient to characterize a planar defect. Corner echo TFM imaging may then be a solution to confirm the non-volume nature of an indication.
With corner echo TFM reconstruction, the time of flight paths (in transmission or reception) consider a single reflection on the background (with or without mode conversion) and the interaction with the defect is a specular reflection. The knowledge of the profile is then necessary: a methodology to measure precisely the internal complex profile of the specimen was developed but is not detailed here. Corner echo mode reconstruction is adapted to reconstruct extended planar defects such as notches. Simulations showed that the LTdT mode was the best corner echo mode to implement in the test case.
Figure 4 shows the LTdT reconstruction of experimental and simulated data from EDM notches of 3mm and 1.5mm high. Simulation and experimental images are in good agreement. The notch is imaged on its entire length and almost the same artifacts of reconstruction can be observed on both simulation and experimental results.
To size of a non-volume indication in corner echo mode, -6 dB amplitude drop sizing may be used carefully (see below). This method has been used to size the notches on corner echo reconstruction mode images of Figure 4. The 3mm high notch has been evaluated as a 2.8mm notch high while the height of the 1.5mm was evaluated as being 1.7 mm. The different results show that sizing of the notch is less accurate in corner echo mode than in direct mode but it remains satisfactory according to the uncertainty of the measurement. Note that the -6dB amplitude drop sizing method on TFM images may not be relevant in all configurations. It may be inaccurate when the defect dimensions are larger than the ultrasonic beam for the mode considered for reconstruction. In this case, the height of the indication could be underestimated.

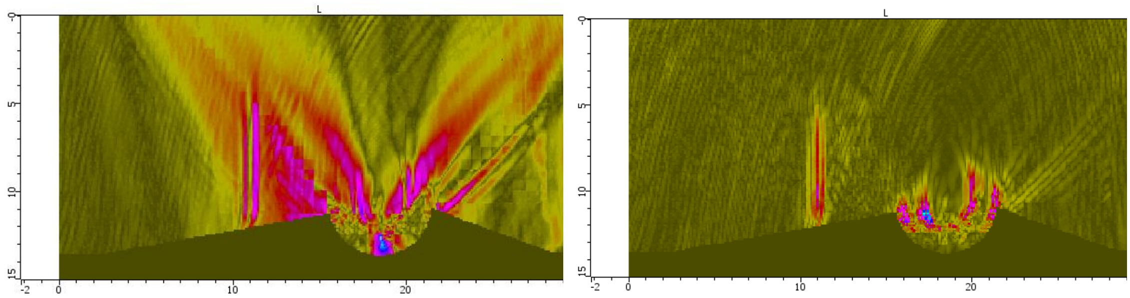


(a) Simulation - LTdT (b) Experiment - LTdT

(c) Simulation - LTdT (d) Experiment - LTdT

Figure 4 : TFM images FTP in LTdT corner mode reconstruction of an EDM notch (a) simulation, h=3 mm, (b) experimental h=3 mm, (c) simulation, h=1.5 mm, (d) experimental h=1.5 mm

These artifacts are associated with nonphysical ultrasound paths used in corner echo mode reconstruction. They are mainly associated with the backwall echo badly reconstructed in corner echo mode. Depending on the probe position and the reconstruction mode, the artifacts may disturb the reading of the acoustic signature of an indication. Therefore, when the probe aperture is located above the bead weld and the defect nearby, its acoustic signature may be mixed with the reconstruction artifact. It is then more difficult to visualize or characterize the flaw. Figure 5(a) illustrates this problem with a notch of 8mm high.

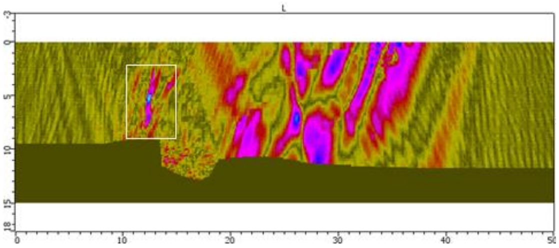
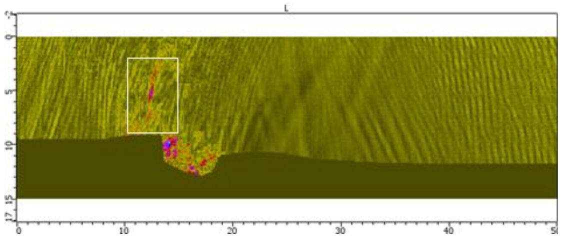


(a) (b)

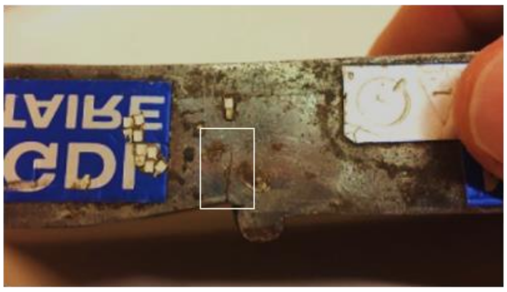
Figure 5 : LTdT TFM image of a notch of 8mm high. The probe is located above the notch (a) no artifact filer is applied, (b) artifact filtering is applied.

There is an option available since CIVA 2016 which allows enhancement of TFM images facing strong artifacts. When activated, this option filters artifacts due to bad reconstruction of the backwall echo in TFM corner echo mode reconstruction. The filtering is based on the elimination of the paths without physical sense. 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 are filtered (3). Applying this option to Figure 5(a) leads to Figure 5(b). The use of the filter reduces strongly the artifacts and makes the notch more visible and easier to characterize.

TFM corner mode imaging has also been evaluated on thermal fatigue crack (Figure 6(c)). The resulting TFM images are reported on Figure 6(a) and (b). They show an acoustic signature that look like the one from a planar defect. This echo is located at the same position as the crack and its direction and height seem to correspond with the ones of the real defect. However, the LTdT image of the crack is less clear than the one of EDM notches. This is due to the geometry of the specimen which surface is twisted (see Figure 1). Indeed, a 2D profile instead of a 3D one was used as input of the reconstruction model. Furthermore, the non-flat surface of the components leads to a non-optimal coupling between the probe and the component surfaces. These approximations and restrictions have a strong impact on the image reconstruction.

(a) (b)



(c)

Figure 6 : LTdT TFM image of a thermal fatigue crack (a) without artifacts filtering, (b) with artifacts filtering

4. Conclusions

This study demonstrated that a methodology using TFM imaging could be implemented using CIVA to enable the detection and characterization of thermal fatigue cracks. Experimental validations are in good agreement with simulation results.

The detection of a crack is possible thanks to TFM direct mode imaging. The detection is ensured if the following echoes are observed:

- A top diffraction echo
- A break in the continuity of the backwall echo if the probe aperture covers the positioning of the breaking defect, or
- A diffraction echo at the bottom of the defect if the opening of the translator does not cover the area where the defect is initiated

Characterization is possible with TFM imaging in direct mode or with the adapted corner echo TFM imaging. Combination of both imaging modes reconstruction allow enhancing characterization diagnosis. The non-voluminal nature of an indication and the fact that it breaks backwall can be confirmed:

- With the direct LL mode when observing a top diffraction echo in addition to a break in the continuity of the backwall echo.
- With the appropriate corner echo imaging mode: in the presence of a planar defect and provided that the profile of the inspected specimen is known, it is possible to reconstruct the flaw along its height.

Sizing is also possible with TFM. In direct mode, measuring the distance between the top and bottom diffraction echoes makes it possible to evaluate very precisely the height of the planar defect. On TFM corner echo images, the -6 dB drop of the amplitude of the acoustic signature can be used to evaluate its height after verification of some restrictions associated with the acoustic beam and the considered corner echo mode (more details in (4)).

EDF CEIDRE can now use the results of this study to implement TFM for workshop tests according to the material and operating recommendations provided by EXTENDE.

Finally, this study has shown that the results simulated with CIVA are in very good agreement with the experimental results. The tools available in CIVA such as profile reconstruction and artifact filtering have shown their ability to improve the quality of reconstructed images but also to improve the characterization of the indications. Simulation of TFM imaging and post-processing of FMC acquisitions with CIVA can therefore be used to predict the results but also to study the parameters influencing this method.

References

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