Advantages and Complementarity of Phased-Array Technology and Total Focusing Method

Frédéric REVERDY 1, Gregoire BENOIST 1, Laurent LE BER 1
1 M2M-NDT, Miniparc du Verger . Bât. H
1, rue de Terre Neuve . 91940 Les Ulis – France
f.reverdy@m2m-ndt.com

Abstract. Total Focusing Method has been recently made available in portable Phased-Array Ultrasonic Instrument. Portable industrial equipment with full-parallel capabilities allows handling of matrix-array probes, 3D imaging and advanced techniques for optimal focusing. Total Focusing Method, a reconstruction based technique, is discussed: it allows better sizing of the defects during inspections, a clear detection of small defects and defect characterization using mode conversion or corner effect mode. Moreover, real-time adaptive inspection associated to Total Focusing Method has been implemented to take into account the variability of the examination surface. During the presentation, results of inspections are presented for industrial relevant applications (Characterization of small defects, Corrosion, HTHA, Porosity detection, crack detection and sizing in welds, blades examinations…). The advantages, drawbacks and the complementarity of different techniques (TFM, Electronic scanning, sectorial scanning, …) will be discussed.

Introduction

Phased-array technology has been accepted for many years and used in many NDE applications thanks to its flexibility and the major improvement in productivity. Instead of the typical amplitude vs time signal, phased-array systems can display ultrasonic data as sectorial or linear images (Sscan or Escan) allowing an inspector to see instantly a complete zone of the component and thus interpret data more easily. These images are obtained by applying time delays to each element of an array probe. Increasingly, more advanced operating modes involving the post-processing of elementary signals are exploited in NDT. A posteriori synthetic focusing of signals, called TFM (Total Focusing Method) is one of the most natural ways of such processing and has been proven to be an efficient way of imaging inspected parts (1) at least for canonical geometries. This method might be applied, at least in theory, to any set of signals, its performances depending obviously of the acquired data. The algorithm has been implemented and extended in the CIVA software to complex geometries and various modes of reconstruction (2). While this technique presents great benefits, one of the main disadvantages is that, up to now, it has been mainly used as a post-processing method making it difficult to apply on the field. M2M has recently developed a portable system, the Gekko, with full-parallel phased-array capabilities that allows real-time TFM reconstruction. This opens the way to new imaging techniques in the field. In this paper we discuss the principles of TFM and show the advantages of this
technique in terms of defect detection and characterization. We also show real-time adaptive inspections associated to TFM that take into account the variability of the examination surface.

1. The Total Focusing Method

1.1 Principle of TFM

The TFM imaging technique can be applied to any acquired data; however in the Gekko it is applied to a dataset recorded from a FMC (Full Matric Capture) acquisition to produce an image in a region of the component. The FMC presents the advantage of maximizing the information available from a given array composed of N elements by sending ultrasonic energy everywhere in the component; this way potential defects can be seen from multiple directions. The FMC acquisition consists in firing each element of the array in turn and recording the information reflected/diffracted in the component on all the elements. The result of the FMC is a NxN dataset composed of every emitter-receiver pair combination of elements in the array. The TFM algorithm consists in coherently summing all the signals \( s_{ij}(t) \) from the dataset to focus at every points of a Region Of Interest (ROI) in a specimen. Mathematically this can be expressed as:

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

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 point P. In the Gekko, this reconstruction is performed in a 256x256 pixels zone with a rate of 25 frames/sec; each pixel corresponding to one of the focused point of the ROI.

1.2 Comparison of sectorial scanning and TFM

Figure 1 shows a comparison between sectorial scanning and TFM for an ASTM E2491 standard mockup. We use a 64-element 5-MHz linear array probe. This calibration mockup has an array of side-drilled holes (SDH) along a 1” radius and another along a 2” radius. For the sectorial scanning we perform a -50–+50° scan with a 0.5° step focusing the energy at 25 mm (1”). For TFM we define a 70x50-mm ROI underneath the surface.

![Fig. 1. Sscan (left) and TFM (right).](image-url)
The SDH located around 25 mm (horizontal dotted line) are clearly detected for both the Sscan and TFM. However, for the Sscan we can see that the echoes clearly show an out-of-focus effect for the SDH located along the 2\(^\circ\) radius. The echoes are elongated and weaker (-17 dB compared to the maximum). For TFM all the SDH are detected at all depths with similar energy (6 dB variation). The advantage is that the operator doesn’t need to specify a depth of focalisation; the TFM offers optimum focusing at every point in the ROI.

1.3 TFM for manual inspection

This ability to focus everywhere is demonstrated on a manual inspection of a laser welded component made of a titanium alloy. The material is composed of large grains ~0.5-1.5 mm and porosities can occur during the welding process. The narrow laser weld is inspected manually which can be an issue and can lead to variations in sensitivity. To evaluate the sensitivity of the NDT technique several hemispherical bottomed holes (HBH) were machined from the side of the sample to finish in the middle of the weld at several depths. We inspected the component with a 32-element 5-MHz linear array with a 75-mm natural focus. We compare sectorial scanning using longitudinal waves focused along the weld (top row) with TFM (bottom row) in Figure 2. For both the Sscan and TFM images we see the echoes obtained at the root of the weld.

In the top left image, we can see the echo obtained at the tip of the HBH; it is detected with a 20 dB Signal-To-Noise (SNR) ratio. To represent an error of positioning during the inspection we moved the probe away from the weld by 4 mm. On the right Sscan, we can see that the echo from the HBH becomes much weaker (5 dB SNR). Because of the
structure of the titanium alloy and the size of the HBH ($\phi = 0.8\text{mm}$) the ultrasonic beam needs to be focused on the defect otherwise the SNR is too small. We see that the sensitivity decreases dramatically when the defect is not in the depth-of-field of the probe.

For TFM, we see that the HBH is detected with a 17 dB SNR for both positions. Because it focuses everywhere in the ROI, TFM is not as sensitive to positioning as sectorial scanning. This can be very important when looking for low-amplitude signal such as porosities or tip diffraction. We see however that the SNR is a little bit smaller compared to the sectorial scan properly focused at the defect. This is due to the fact that data acquired to perform the TFM were obtained using a FMC meaning that element were fired one by one. This could lead for some cases to lower amplitude signals, particularly when the elements are small.

By focusing everywhere within the ROI the TFM offers an ease of use for operators/experts; they don’t have to worry about the depth of focalization.

2. Multi-mode TFM

2.1 Multi-mode imaging

In a wide range of NDT applications crack-type defects located close to the backwall of a component are detected by exploiting a corner effect that involves a reflection off the backwall. TFM images in previous figures were obtained using a direct mode, i.e, only the direct path from each emitter to each point of the ROI and back to each receiver was considered. TFM imaging can also be done taking into account reflexion and/or conversion off other boundaries such as the backwall. TFM imaging implemented in the Gekko offers three imaging modes shown in Figure 3: direct, corner echo (each one can be done using the longitudinal or transverse waves) and indirect imaging (mode conversion).

![Fig. 3. Scheme of the different TFM imaging modes: a) direct imaging, b) corner echo imaging, c) mode conversion imaging.](image)

The notation is the following: letters L and T designate longitudinal and transverse waves, respectively. For direct TFM, the first letter corresponds to the path between the transmitter and the focused point, the second letter corresponds to the path between the focused point and the receiver. For corner echo and mode conversion, the first letter corresponds to the path between the transmitter and the backwall, the second, the path between the backwall and the focused point, and the third letter, the path between the focused point and the receiver.

Figure 4 shows examples of direct, corner echo and mode conversion TFM imaging for various 10-mm notches: a surface-breaking notch located along the backwall, a notch located in the middle of the plate and a surface-breaking notch located along an angled backwall surface. The FMC acquisition has been performed in contact with a 5-MHz, 64 element linear array transducer.
For the LL mode, we can see that tip diffractions are visible even when the extremity of the defect is located along the backwall surface. Corner and mode conversion images give a different representation of the defects; the defect profiles are reconstructed along their entire length. Moreover, the Signal-To-Noise ratio (SNR), compared to the strongest diffraction echo of the corresponding LL mode, is higher making TFM a strong tool for defect characterization particularly in noisy materials for which the SNR for tip diffraction might not be enough. These results show that multi-mode TFM provides complementary indications about the defects and therefore, the combined use of different imaging modes offers great potential for defect characterization in terms of size, nature and orientation. The Gekko allows switching from one mode to another by simply recomputing the delay laws associated to that particular mode, which takes a couple of seconds. Perfect knowledge of the sample thickness and velocity is however required for corner and mode conversion images.

2.2 Surface breaking cracks

Surface defects are among the most common flaws occurring in structural components and consequently it is important for design office to know their shape when one is detected. While it is very common to assume rectangular shapes for calibration defects, surface defects in semi-infinite plates usually tend towards semi-circular profiles whilst in finite plate they start growing in approximately a semi-elliptical manner. When detecting this type of defects with sectorial scanning it is difficult to characterize them properly. Indeed, it is difficult to apply a -6-dB rule because of the shape of the defects and diffraction echoes are not always observed across the entire width of the defects. Figure 5.a shows the Dscan of a 2-mm high semi-elliptical EDM notch obtained during a standard sectorial scan inspection; the theoretical shape of the defect is superimposed as a dotted line. One can see a corner echo across the entire width of the defect while a diffraction echo is only observed close to the center of the defect.
Two Sscans are extracted; number 1 is taken at the centre of the defect while number 2 is taken off that centre. In Figure 5.b, it is possible to detect both corner and diffraction echoes making it possible to measure the height of the defect for that location. For Figure 5.c, only the corner echo is observed. For that position, the diffracted energy is not contained in the same plane as the incident one and is not detected by the probe making sizing impossible outside of the centre region of the defect.

Using the same probe we performed a FMC acquisition - TFM reconstruction using the TTT corner echo mode. Results are displayed in the following figures as a Dscan and two TFM images for the same positions 1 and 2. Again, the theoretical profile of the defect is superimposed to the DScan as a dotted line. One can see that the Dscan shows directly the shape of the semi-elliptical defect. TFM images obtained for positions 1 and 2 show two vertical profiles; the height of those profiles is proportional to the height of the semi-elliptical defect for those positions.

We see here several advantages of multi-mode TFM:
- sizing can be possible for small defects for which it is typically not possible to get a diffraction. The precision depends on the wavelength and the aperture of the array
- characterization is possible for defects that don’t have an edge perpendicular to the focal plane of the probe.

**Adaptive TFM**

The reconstructions presented above were performed for components with flat surfaces. For complex geometries with an irregular entry surface, such as a corroded surface, the ultrasonic field can be distorted making the detection of potential defects impossible. Phased-array technology offers the ability to perform inspection under complex surfaces by adjusting delay laws to take into account the variations of the entry surface. However the geometry of the surface needs to be perfectly known, which is not always the case.
CEA and M2M developed and implemented in the Gekko a real-time adaptive process, called ATFM (Adaptive TFM), that measures first the entry surface then performs a TFM reconstruction underneath the complex surface \(^{(6)}\).

We describe here the various steps of the ATFM process.

1. A ROI is defined at an approximate distance equivalent to the water path
2. A TFM reconstruction is performed in a semi-infinite medium using the velocity of water
3. The profile of the entry surface is extracted by detecting the maximum of the envelop in each column of the TFM image
4. A TFM inside the component can be calculated taking into account the measured profile to adjust the delays and focus at each point of a ROI inside the component.
5. The profile of the front surface and the TFM reconstruction are displayed by the Gekko in real time.

We used this technique with a local immersion probe composed of a standard linear phased-array probe attached to a flexible wedge filled with water. The mockup is a 30-mm thick aluminium block containing two pairs of 10-mm wide notches and one 2-mm SDH; an irregular surface was machined above one set of defects. Figure 7 shows a side view of the mockup and TFM reconstructions with the adaptive process disabled and enabled.

![Fig 7](image_url)

Fig 7. Adaptive TFM on an aluminium mockup with irregular surface.

One can see that when the adaptive process is disabled only the defects located underneath the flat surface can be detected. Even the backwall is not detected when located underneath the wavy surface. This is due to the fact that the times-of-flight are not properly calculated to take into account the variation of the front surface. When the process is enabled, the profile of the front surface is reconstructed correctly; one can compare the “measured surface” in the third image to the front surface of the mockup in the first image. Using the information from this “measured surface” the TFM algorithm is able to detect all the defects even those located underneath the irregular part of the entry surface in real time.

The adaptive process was then applied to the thickness measurement of a welded pipe. A 64-element, 10-MHz probe was used over a 12-mm thick pipe. An image of the welded pipe is displayed in figure 8.a. The image on the right shows a screen capture of the adaptive reconstruction using the Gekko. One can see the reconstructed profile of the weld crown and the TFM image of the backwall surface taking into account the front surface.
profile. The accuracy of the thickness measurement is about 0.5 mm for that particular configuration.

![Image](image_url)

**Fig 8.** Weld pipe side view (a) and corresponding adaptive TFM (b)

One can also see echoes in the weld that could be associated to potential defects. Without reconstruction of the front surface it would have been impossible to detect those echoes. ATFm offers huge potential for the inspection of components that requires polishing the entry surface to remove a weld cap for example. This could lead to big time and cost savings.

**Conclusions**

Total Focusing Method is a technique that has been used for quite some time. However, it was limited to post-processing making it difficult to apply it in the field. Recently, portable phased-array systems have been made available with TFM capabilities. In this paper, we showed some TFM results using direct and corner echo modes and showed some of the advantages of TFM over sectorial scanning. Because of its ability to focus everywhere, TFM is less sensitive to positioning and easier to use. TFM allows characterization of small defects and complex defects where standard phased-array could not. Corner echo modes can also improve the SNR, which could be important in noisy material. However, we see that TFM can potentially lead to lower amplitude echoes when the size of the elements is relatively small. Finally, we showed the potential of TFM to perform reconstruction below complex surfaces such as a weld. This opens the way for inspections for which the surface is not known (after hand machining for example) and inspection of welds from the weld crown.

**References**