Adaptive Ultrasonic Imaging with a Phased-array Probe Equipped with a Conformable Wedge

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Abstract. In the present paper, some improvements of the real-time adaptive Total Focusing Method (TFM) are proposed. The surface imaging with TFM is enhanced by reducing the computation time, as well as the imaging artifacts associated with aliasing effects. Next, it is demonstrated that the adaptive focusing principle can be generalized to inclined array probes above complex surfaces. An application of such a development is the real time inspection of irregular surface specimens with angled conformable elastomer wedges. Experimental TFM images with L0°, L45° and T45° conformable wedges are given.

Introduction

Immersion ultrasonic testing of components with irregular geometries may be dramatically enhanced with the help of transducer arrays associated with adaptive imaging algorithms able to image flaws without accurate information about the geometry. The principle of immersion adaptive methods can be described in two key-steps [1]. First, the geometry of the surface is acoustically determined by recording and processing the water/solid interface echoes. Second, a ray-based forward model is used to calculate the wave travel times from the array elements to the region of interest in the material. A delay-and-sum algorithm can then be applied to focus everywhere under the complex interface.

The CEA-LIST has developed an adaptive imaging method based on the Total Focusing Method (TFM) [2,3]. The so-called ATFM (Adaptive TFM) has been recently implemented in the M2M portable systems (Gekko) for real time inspections of complex structures with a high image quality [4]. In this approach, the full array response matrix is recorded, and processed twice to obtain the final image. The TFM is first applied to the data set to image the surface and to extract its geometry. Once the surface geometry has been determined, a second TFM image is calculated in the specimen by processing the same data with the inter-element times of flight calculated for all the pairs of transmitter/receiver and all the focusing points below the complex surface.

The present paper summarizes improvements brought by the CEA-LIST to the ATFM, in the context of a collaborative program with EDF and AREVA. The aim of this work is to
optimize the ATFM algorithms in order to control specific structures proposed by EDF and AREVA. One of the objectives of this program is to associate the adaptive TFM imaging with a new immersion local control solution developed by the Imasonic Company. The device consists of a conventional array probe equipped with a conformable elastomer wedge filled with water. In the present paper, improvements are brought to the calculation of the surface image in order to reduce the computation time and to filter imaging artifacts related to aliasing effects in water. Next, it is shown that the adaptive focusing algorithms remain valid with angled conformable wedges to perform L45° and T45° inspections.

Theoretical background in TFM imaging

1.1 Imaging algorithm for a contact transducer array

The TFM algorithm is applied to the full array response matrix \( K(t) \) composed of the \( N \times N \) inter-element impulse response \( k_{pq}(t) \) of a transducer array with \( N \) elements. The post-processing algorithm focuses in both transmit and receive modes the set of \( N \times N \) analytic signals \( s_{pq}(t) = k_{pq}(t) + jH[k_{pq}(t)] \) at every point of a region of interest (\( H \) denotes the Hilbert’s transform). With the notations described in Fig. 1a, the TFM imaging equation can be written as

\[
A(\vec{r}) = \left[ \sum_{p=1}^{N} \sum_{q=p}^{N} (2 - \delta_{pq}) \mu_p(\vec{r}) v_q(\vec{r}) s_{pq} [t_{pq}(\vec{r})] \right],
\]

where \( \vec{r} \) is the position vector of the focusing point \( M(x, z) \). The Kronecker’s symbol \( \delta_{pq} \) (\( \delta_{pq} = 1 \) if \( p = q \), \( \delta_{pq} = 0 \) otherwise) is introduced to take into account the reciprocity principle in the image calculation, i.e. \( k_{pq}(t) = k_{qp}(t) \). This reduces the number of sums from \( N \times N \) to \( N \times (N + 1)/2 \) at every focusing point. \( \mu_p(\vec{r}) \) and \( v_q(\vec{r}) \) are apodization or weighting factors introduced to filter imaging artifacts (due to aliasing effects, aperture edge diffraction effects, geometry echoes…) [5]. In imaging with direct propagation modes, the inter-element time of flight \( t_{pq}(\vec{r}) \) for a contact transducer array is simply given by

\[
t_{pq}(\vec{r}) = \frac{\| \vec{r} - \vec{r}_p \| + \| \vec{r} - \vec{r}_q \|}{c},
\]

where \( c \) is the velocity of the longitudinal (L) or transverse (T) waves in the medium.

Figure 1: 2D imaging geometry used for the TFM formulation: contact array (left); immersion array above a complex water/solid interface described by \( Z = S(X) \) (right).
1.2 Imaging algorithm for an immersion transducer array

When a transducer array is immersed in water above a specimen with an arbitrary surface described by \( Z = S(X) \) (see Fig 1b), the inter-element propagation time from a transmitter \( p \) to a receiver \( q \) can be decomposed as follows

\[
t_{pq}(\vec{r}) = \frac{\|\vec{r}^S_p - \vec{r}_p\|}{c_1} + \frac{\|\vec{r}^S_q - \vec{r}_q\|}{c_2} + \frac{\|\vec{r} - \vec{r}^S_q\|}{c_1} + \frac{\|\vec{r} - \vec{r}^S_q\|}{c_2},
\]

where \( c_1 \) and \( c_2 \) (\( c_2 = c_t \) or \( c_2 = c_T \)) are the wave velocities in water and in solid. \( \vec{r}^S_p \) (resp. \( \vec{r}^S_q \)) is the position vector of the intersection point \( S_p^M \) (resp. \( S_q^M \)) between the surface \( S(X) \) and the ultrasonic ray coming from transmitter \( p \) (resp. \( q \)) to the focusing point \( M(x, z) \). In TFM imaging with LL or TT direct propagation modes, \( t_{pq}(\vec{r}) \) satisfies the reciprocity principle, \( t_{pq}(\vec{r}) = t_{qp}(\vec{r}) \), so that the problem can be reduced to the calculation of the propagation time from a transmitter \( p \) to the focusing point

\[
t_p(\vec{r}) = \frac{\|\vec{r}^S_p - \vec{r}_p\|}{c_1} + \frac{\|\vec{r} - \vec{r}_p\|}{c_2}.
\]

According to the Fermat’s principle, the wave propagation through the water/solid interface must correspond to the minimum propagation time. Therefore, by developing the Euclidean norms in Eq. (4) with \( \vec{r} = (x, z) \), \( \vec{r}^S_p = (X; S(X)) \), \( \vec{r}_p = (x_p, 0) \), the Fermat’s principle leads to the determination of the surface point (absissa \( X \)) that minimizes the function:

\[
f_p(X) = \frac{1}{c_1} \sqrt{(X - x_p)^2 + S^2(X)} + \frac{1}{c_2} \sqrt{(X - x)^2 + S^2(X) - z^2}.
\]

In the context of embedded processing in portable systems, one of the most efficient algorithms in terms of simplicity and robustness is the gradient descent method

\[
X^{(k+1)} = X^{(k)} - f_p'(X^{(k)}) / f_p''(X^{(k)}).
\]

The exponent ‘(k)’ (\( k \in \mathbb{N} \)) denotes the iteration step (\( X^{(0)} \) is the starting value of \( X \)). \( f_p'(X) \) and \( f_p''(X) \) are the first and second derivatives of \( f_p(X) \) with respect to \( X \). They are numerically calculated with finite differences to accelerate processing times. The starting value is set equal to the element absissa \( X^{(0)} = x_p \) because the wave velocity in water is significantly lower than the ones in solid. It should be noted that this focusing algorithm is quite general and remains valid for various geometries (except in presence of caustics or significant surface discontinuities). It can be extended to 3D geometries.

Adaptive TFM (ATFM) for immersion testing

2.1 Surface imaging and profile measurement

The first step of the adaptive TFM is the calculation of an image of the surface in front of the array aperture considering ultrasound propagation in water. The surface profile \( Z = S(X) \) is extracted from the image by detecting the maximum amplitude along each column. Then, the profile is smoothed and interpolated before focusing inside the
specimen. For an image of width \( L_x = n_x \Delta_x \) and height \( L_z = n_z \Delta_z \) (\( \Delta_x \) and \( \Delta_z \) are the calculation steps along \( L_x \) and \( L_z \)), the total number of sums to be calculated with Eq. (1) is

\[ N(N + 1)(n_x + 1)(n_z + 1)/2, \]

which leads to long computation times for large arrays and extended images. This is why the values of \( \Delta_x \) and \( \Delta_z \) have to be appropriately chosen to minimize the number of points, while preserving the TFM image quality in water. Let \( D = Nd \) be the array aperture (\( d \) is the pitch), \( f_c \) the transducer center frequency, and \( H \) the mean water path above the surface. Hence, the step \( \Delta_x \) can be defined as the lateral resolution at \( H \): \( \Delta_x = c_1 H/(f_c D) \). The step \( \Delta_z \) is related to the signal sampling frequency \( f_e \) and must satisfy the Shannon’s criterion, i.e. \( f_e \geq 2f_{\text{max}} \). With \( f_e = 2f_{\text{max}} \), the value of \( \Delta_z \) can be set equal to \( \Delta_z = c_1/(4f_{\text{max}}) \) where \( f_{\text{max}} = f_c(1 + BW/2) \) and \( BW \) is the mean element bandwidth. A TFM image calculated with such a spatial sampling preserves the surface echoes and it is not necessary to add more calculation points. It can be noticed that the TFM image grid is thinner in the \( Z \)-direction (\( \Delta_x \propto 1/f_e \)) than in the \( X \)-direction (\( \Delta_z \propto 1/f_e \)) since the profile measurement is more sensitive to an incorrect time sampling.

In addition to the reduction of the number of focusing points, a significant set of signals \( k_{pq}(t) \) can be ignored in the \( K(t) \) matrix. As the surface is close to the array and the radiation pattern of an element is more directional in water than in solid, a signal \( k_{pq}(t) \) corresponding to a pair of transmitter \( q \) and receiver \( p \) distant from each other (\( \| \vec{r}_q - \vec{r}_p \| \gg d \) does not bring a significant contribution to the surface image. Therefore, only the signals received by a sub-array centered on the transmitter can be processed in Eq. (1). If \( n = 2m + 1 \) (\( m \in \mathbb{N} \)) is the number of elements in each sub-array, the TFM imaging equation can be rewritten as:

\[
A(\vec{r}) = \left\{ \begin{array}{ll}
\sum_{p=1}^{N} \sum_{q=p}^{p+m} (2-\delta_{pq}) \mu_p(\vec{r}) v_q(\vec{r}) s_{pq} f_{pq}(\vec{r}) & \text{if } p+m \leq N \\
0 & \text{if } p+m > N
\end{array} \right. \tag{6}
\]

Both the receive sub-arrays and the reciprocity principle are considered in Eq. (6), so that the second sum over the transmitter indexes \( q \) now includes \( m + 1 \) terms, instead of \( N \) in TFM imaging without optimization. The data volume reduction in the \( K(t) \) matrix is shown in Fig. (2). From the full matrix containing \( N \times N \) signals, a triangular \( K'(t) \) matrix with \( N \times (N + 1)/2 \) signals is obtained when the reciprocity principle is taken into account. The receive sub-arrays leads to a new sparse \( K''(t) \) matrix with only \( (N - m/2) \times (m + 1) \) inter-element signals. For instance, for a transducer array with \( N = 64 \) elements and sub-arrays of \( n = 33 \) receivers (\( m = 16 \)), the data volume is reduced by 75% compared to the complete \( K(t) \) matrix.

Figure 2: Full matrix \( K(t) \) composed of \( N \times N \) signals (a); triangular matrix \( K'(t) \) with \( N \times (N + 1)/2 \) signals resulting from the reciprocity principle (b); sparse matrix \( K''(t) \) with \( (N - m/2) \times (m + 1) \) signals when receive sub-arrays of \( n = 2m + 1 \) are considered.
In Eq. (6), weighting factors are introduced in order to limit the imaging artifacts associated with grating lobes. The conventional probes used in immersion testing are designed with a pitch satisfying \( d \leq \lambda_2 \), where \( \lambda_2 \) is the wavelength in the solid medium. This ensures that the grating lobes are far from the main beam, but this is not the case in water where \( d > \lambda_1 \) (for a typical 5-MHz array probe with \( d = 0.6 \) mm, the wavelength in water is \( \lambda_1 = 0.3 \) mm and the first grating lobes appear at \( \pm 30^\circ \) around the main lobe). The weighting factors limit these aliasing effects in water by attenuating the image points associated with large transmit and receive angles. These factors are chosen to be identical in transmit and receive modes \( \mu_p(\vec{r}) = \nu_q(\vec{r}) \) and correspond the directivity function of a rectangular element. It is defined by [6]

\[
\mu_p(\vec{r}) = \text{sinc}
\left[ k_1 \frac{a}{2} \sin \theta_p(\vec{r}) \cos \theta_p(\vec{r}) \right],
\]

where \( a \) is the element width, \( k_1 = \omega/c_1 \) is the wavenumber in water, and \( \theta_p(\vec{r}) \) is the transmission angle from an element \( p \) to the point image

\[
\theta_p(\vec{r}) = \sin^{-1} \left( \frac{\vec{r} - \vec{r}_p}{\|\vec{r} - \vec{r}_p\|} \cdot \hat{x} \right)
\]

In Fig. 3, the TFM algorithm is successively applied to the matrices \( \mathbf{K}'(t) \) and \( \mathbf{K}''(t) \) to measure the weld surface of a steel specimen. The linear array consists of 64 elements (with \( d = 0.6 \) mm and \( a = 0.5 \) mm) that operate around 5 MHz (the – 6 dB bandwidth is \( BW = 80\% \)). For more clarity and brevity, the same probe characteristics will be considered throughout the paper. The surface image in Fig 3a calculated with \( \mathbf{K}'(t) \) (and no amplitude weighting) emphasizes significant imaging artifacts due to the aliasing effects, which leads to an important error in the profile extraction around \( X = 5 \) mm. The calculation of the second image in Fig. 3b requires only 25 % of the \( N \times N \) signals (the sub-arrays consist of \( n = 33 \) receivers), and the directivity functions now are taken into account in Eq. (6). The noise due to aliasing effects is significantly filtered and the surface profile is correctly measured. It is important to note that the principle of focusing in receive mode with sub-arrays also limit the imaging artifacts because the secondary beams reflected by the surface propagate outside of sub-apertures, and thus are not recorded. The TFM algorithm applied to \( \mathbf{K}''(t) \) without amplitude weighting should provide a result close to the one displayed in Fig. 3a.

Figure 3: TFM images of a complex surface and measured profiles (in white continuous lines): imaging algorithm applied to the triangular matrix \( \mathbf{K}'(t) \) (a); imaging algorithm with weighting factors applied to the sparse matrix \( \mathbf{K}''(t) \) (b).
2.2 Imaging below the complex surface

The main difficulty in the immersion adaptive methods lies in the fact that only a local surface is measured below the array aperture, while the geometry on both sides is not assumed to be known during a real time inspection. A parametric study was conducted with the CIVA simulation software for different probe characteristics and surface geometries, and this study shows that \( L_x \leq D \) for any configuration inspection, where \( L_x \) is the orthogonal projection of the measured surface \( S(X) \) onto the \( X \)-axis. This limited size of the measured profile leads to the problems described in Fig 4: when \( L_x < D \), some elements of the probe are located above an unknown surface (see Fig. 4a); when the image area is larger than \( L_x \), or when it is not centered on the array axis (see Fig. 4b schematizing a \( L45^\circ \) inspection with TFM), a significant set of focusing points are located below an unknown surface.

The specificity of the adaptive TFM can be better understood with the ray tracing in Fig. 5a for a \( L0^\circ \) inspection type. The transmitter \( E_p \) is located above an unknown surface but the ray \( (E_pM) \) for an image point \( M \) is a physical path and must be taken into account in the image calculation because it intersects the measured surface \( S(X) \).

![Figure 4: Examples of inspection configurations where some array elements and/or image points are located in front of a non-measured surface: \( L0^\circ \) inspection where \( L_x \leq D \) (a); \( L45^\circ \) inspection where the TFM image area is not centered on the array axis (b).](image)

![Figure 5: \( L0^\circ \) inspection configuration: non-physical propagation path between a transmitter \( p \) and a receiver \( q \) due to the limited size of the measured surface (a). Map of the number of summed signals at every pixel of the TFM image (b).](image)
On the contrary, the receiver \( E_q \) is above the measured surface, but the associated ray \( (E_q M) \) is a non-physical path that does not intersect \( S(X) \). Therefore, the inter-element time of flight from \( E_p \) to \( E_q \) must not be taken into account in the image calculation, which means that the analytic signal \( s_{pq}(t) \) in Eq. (1) is equal to zero if \( t = t_{pq}(\vec{r}) \) (\( \vec{r} \) is the position vector of \( M \)). In the gradient descent method used for the determination of the minimum propagation times, the solution \( Z^{(k)} = S(X^{(k)}) \) given by the iterative algorithm must belong to \( S(X) \). If an element is not located above \( S(X) \), the starting point \( Z^{(0)} = S(X^{(0)}) \) of the iterative algorithm is determined with a linear extrapolation of the surface. The map in Fig. 5b displays the number of physical paths passing through the measured surface (the maximum number is \( 64 \times 65/2 = 2081 \)) at every point of the TFM image in an aluminum specimen with a plane surface (with \( H = 20 \) mm and \( L_x = 0.75D \)). This map can also be interpreted as the number of summed signals in Eq. (1) at every pixel. It can be noted that the number of signals significantly varies in the region of interest (it is reduced by almost 40% at the right and left edges of the image). This is a main difference with the conventional TFM imaging where a same number of signals is processed everywhere in the image area.

### Experimental results with L45° and T45° immersion probes

The adaptive TFM imaging was experimentally evaluated with various specimens and probes. In particular, the method was associated with a new immersion control solution developed by the Imasonic Company. It consists in a conventional transducer array probe equipped with an elastomer conformable wedge filled with water. The probe is furnished with a set of different angled wedges according to the desired inspection configuration: \( L^0° \), \( L^45° \), \( T^45° \)… For angled wedges, the method proposed in this paper remains practically unchanged; the only difference lies in the calculation of the propagation paths that now depends on the inclination angle \( \alpha \) of the array. The new function to be minimized with the gradient descent method is

\[
f_p(X) = \frac{1}{c_1} \sqrt{(X-x_p \cos \alpha)^2 + [S(X)+z_p \sin \alpha]^2} + \frac{1}{c_2} \sqrt{(X-x)^2 + [S(X)-z]^2},[9]
\]

with \( \alpha \geq 0 \). The starting value must to be changed in order to accelerate the convergence of the iterative algorithm. A satisfying value of \( X^{(0)} \) is:

\[
X^{(0)} = x_p \cos \alpha + [S(x_p \cos \alpha) + x_p \sin \alpha] \tan \alpha.
\] [10]

Experimental results are given in Fig. 6 for two inclination angles, \( \alpha = 10.4° \) and \( \alpha = 19.2° \), that correspond to refractions around 45° in an aluminium medium with \( L \) or \( T \) waves. For each probe inclination, the TFM images are displayed below a plane surface and a complex one, and the results can be compared with each other by examining the echoes of a 6-mm height notch. In both cases (\( LL \) and \( TT \) direct modes), the notch images below the plane and complex surfaces are similar, except the corner echo that is slightly more spread due to the particular shape of the surface. For all the results in Fig. 6, it is quite surprising to observe that the notch is correctly imaged, whereas the measured surface has a limited size compared to the probe aperture and the image area is far from the array axis. However, it can be shown that the number of summed signals remains large because of the favourable orientation of the probe (the number of ignored signals is less than 30%).
Figure 6: TFM images of a 6-mm breaking notch in an aluminum mock-up with two orientations of the array: $LL$ images with a $10.4^\circ$ inclination angle for plane (a) and complex surfaces (b); $TT$ images with a $19.2^\circ$ inclination angle for plane (c) and complex surfaces (d).

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References