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Plane Wave Imaging for ultrasonic non-destructive testing: Generalization to multimodal imaging

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ABSTRACT

This paper describes a new ultrasonic array imaging method for Non-Destructive Testing (NDT) which is derived from the medical Plane Wave Imaging (PWI) technique. The objective is to perform fast ultrasound imaging with high image quality. The approach is to transmit plane waves at several angles and to record the back-scattered signals with all the array elements. Focusing in receive is then achieved by coherent summations of the signals in every point of a region of interest. The medical PWI is generalized to immersion setups where water acts as a coupling medium and to multimodal (direct, half-skip modes) imaging in order to detect different types of defects (inclusions, porosities, cracks). This method is compared to the Total Focusing Method (TFM) which is the reference imaging technique in NDT. First, the two post-processing algorithms are described. Then experimental results with the array probe either in contact or in immersion are presented. A good agreement between the TFM and the PWI is observed, with three to ten times less transmissions required for the PWI.

1. Introduction

Ultrasonic transducer arrays are more and more used for industrial Non-Destructive Testing (NDT). Compared to single element transducers, they are much more versatile as they allow different inspection modes (plane waves, steered angle beams, focused beams) and can be used to produce images (focused Bscans, focused Sscans [1,2]) at a single position. In array imaging, one of the best method is the Synthetic Transmit Aperture (STA [3,4]), also called Total Focusing Method (TFM) in the NDT field [5]. This method is based on the post-processing of the full array response matrix $\mathbf{K}(t)$ [6], called Full Matrix Capture (FMC) in NDT. For a N element transducer, the FMC consists in recording the $N \times N$ inter-element impulse responses $k_{ij}(t)$, defined as the signal received by element j when an electric pulse is applied to element i. The TFM allows to focus on every point of the image area while, in the focused Sscans and focused Bscans modes, the image is constructed line by line and by focusing at a given depth. This technique has several advantages compared the other imaging methods (focused Sscans, focused Bscans). The main advantage of the TFM is the image quality as the focusing and spatial resolution are optimal everywhere in the region of interest. Another benefit is the possibility of applying different imaging modes to the same array response matrix, depending on the nature of the defects [7–9]. For example, images can be made using half-skip paths, including a reflection on the back-wall before interacting with the defect, to image crack-type defects. Finally, unlike in focused Bscan, the TFM image area can be larger than the probe and is not related to the number of shots, contrarily to focused Sscan images. However, the TFM technique has two main drawbacks. The first one is a limited acoustic power sent into the medium due to the use of only one element per emission. This results in a degradation of the signal to noise ratio (SNR) and can be troublesome in the case of attenuating materials and random noise. Moreover, controls looking for crack-type defects are made typically around 45°, thus the image is not centered under the probe. In this situation, the cylindrical wave emitted by an element, radiating mainly perpendicularly to the transducer plan, is not the most fitted type. In some cases, this is highlighted by the existence of non-physical indications, also called image artifacts, that may lead to misinterpretations [10,11]. The second drawback is the frame-rate limit due to the number of transmissions (N) and the storage and processing of the $N \times N$ signals. Techniques exist to reduce the number of signals to be processed, like the Sparse Matrix Capture (SMC) that uses a few elements in transmission, compensating the loss of acoustic power by creating virtual sources [12–15].

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In order to improve the frame-rate and increase the acoustic power sent into the medium, the Plane Wave Imaging (PWI [16–18]), recently developed in the medical field, seems to be very promising for NDT inspections. The principle is to transmit plane ultrasonic wave-fronts at different angles in the medium. For each plane wave transmission, the PWI image is reconstructed line by line by dynamically focusing in receive mode at different depths with a subset of several adjacent receivers. The final image is then obtained by summing the images obtained for every angle. This method has several advantages in medical imaging. The main advantage is a high image quality obtained with a few ultrasonic shots (typically 10 to 30 for a 128 elements probe). Furthermore, as all the probe elements are excited together, the acoustic power sent in the medium is high. Thus, this method is less sensitive to attenuation and random noise than the TFM. The main drawback is that the image size is limited by the probe aperture. The number of lines in the image depends on the number of elements, and a classical NDT inspection uses transducers with 32 to 64 elements. Thus the number of elements and, therefore, the image size are too small to perform accurate inspections. Moreover, the PWI used in the medical field cannot image crack-type defects. This is due to the fact that subsets of elements are used in reception, while crack-type defects imaging requires reception on all the probe elements to use half-skip modes.

In this paper, we present a technique that combines the advantages of the PWI and the TFM. The main objective is to prove that high quality images can be obtained by the transmissions of plane waves. The second goal is to explore the possibility to reduce the number of transmissions and to limit imaging artifacts due to mode conversions. The medical PWI is generalized by taking into account the refraction on a plane interface, the bulk wave polarizations (longitudinal: *L*, transverse: *T*) and the paths including interactions with the back-wall (half-skip modes). In transmission, plane waves are emitted at different angles and the backscattered signals are recorded by the elements. Thus creating a $Q \times N$ matrix where Q is the number of plane waves transmitted and N is the number of elements in the probe. This matrix is then post-processed to perform beamforming in transmit and receive modes. This method will allow multi-modal PWI imaging (direct and half-skip modes) with high acoustic power sent into the inspected material and low acquisition time. In the first section, the theoretical backgrounds of the multi-modal TFM and PWI methods are presented. The second section presents and compares experimental results obtained with the two methods for different types of defects.

2. Theoretical background

This section describes the theoretical backgrounds of the Total Focusing Method (TFM) and Plane Wave Imaging (PWI) techniques. For a general description, we consider an immersion configuration, where the array and the specimen are immersed in water. First, they are derived for simple round-trip, also called direct modes. In these modes, the wave goes from the transmitter to the focusing point and back to the receiver. Then, they are generalized to half-skip mode reconstructions in which the wave goes from the transmitter to the focusing point after reflection on the back-wall, and back to the receiver. The direct modes are useful to image volumetric flaws (holes, porosities, inclusions) while half-skip modes are used to enhance the characterization of crack-type defects.

2.1. TFM algorithm

The TFM imaging technique is applied to the full array response matrix $\mathbf{K}(t)$. This matrix contains the $N \times N$ inter-element impulse responses $k_{ij}(t)$, corresponding to the signal received by element j when an electric pulse is applied to element i. The TFM consists in coherently summing all the analytical signals $s_{ij}(t) = k_{ij}(t) + jH(k_{ij}(t))$, where H is the Hilbert's transform [5]. Thus, the ultrasonic beam is focused on every point of a region of interest (ROI). Considering a point P in the ROI, the amplitude $A(P)$ at this point is given by:

$$A(P) = \left| \sum_{i=1}^{N} \sum_{j=1}^{N} s_{ij}(t_i^P + t_j^P) \right|, \tag{1}$$

where t_i^P (resp. t_j^P) is the time of flight between transmitter i (resp. receiver j) and point P. The difficulty of the method lies in the determination of the times of flight where the refraction at the interface between the coupling medium (water) and the inspected material (steel) has to be taken into account.

2.1.1. Imaging with direct modes

In direct mode, the ultrasonic wave propagates from a transmitter to the focusing point and back to a receiver, through the surface (Fig. 1).

For the incident path, the wave goes from the transmitter $i(x_i, 0)$ to the impact point $I_{in}(x_{in}, z_{in})$ on the surface at the sound velocity in water v_a. Then it propagates from I_{in} to the focusing point $P(x_P, z_P)$ with the velocity v_b, which can be the velocity of the longitudinal (v_L) or transverse (v_T) waves, depending on the type of wave used. The outgoing path follows the same pattern, the wave going from the focusing point P to the impact point $I_{out}(x_{out}, z_{out})$ with the celerity v_c (v_L or v_T) and then from I_{out} to $j(x_j, 0)$ with the sound speed v_a. The following demonstration focus on the incident wave because, for a pair element/focus point, the paths in transmission and in reception are identical. The time of flight corresponding to the incident path is given by:

$$t_i^P = \frac{\sqrt{(x_{in} - x_i)^2 + z_{in}^2}}{v_a} + \frac{\sqrt{(x_P - x_{in})^2 + (z_P - z_{in})^2}}{v_b}. \tag{2}$$

The Fermat's principle states that the physical path corresponds to the minimum time of flight, which can be estimated by finding the zeros of the first derivative of t_i^P with respect to x_{in}. This is equivalent to solve the Snell-Descartes law of refraction:

$$\frac{v_b}{v_a} \frac{(x_{in} - x_i)}{\sqrt{(x_{in} - x_i)^2 + z_{in}^2}} - \frac{(x_P - x_{in})}{\sqrt{(x_P - x_{in})^2 + (z_P - z_{in})^2}} = 0. \tag{3}$$

For a plane interface, by squaring Eq. (3), an analytical solution can be obtained by Ferrari's method [19]. A more general approach, also available for more complex surfaces, is to solve Eq. (3) using an

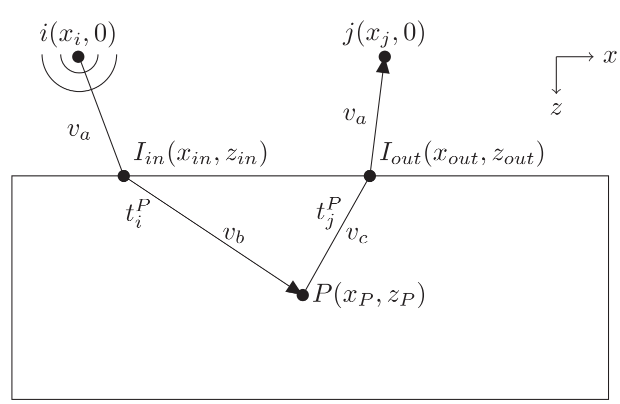

Fig. 1. Illustrations of the paths followed by a wave in direct mode TFM imaging. The cylindrical wave transmitted by element i propagates to the focus point P through the surface at I_{in}, and back to receiver j through the surface at I_{out}.