Ultrasonics 48 (2008) 636–642

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Advanced post-processing for scanned ultrasonic arrays: Application to defect detection and classification in non-destructive evaluation

Caroline Holmes, Bruce W. Drinkwater *, Paul D. Wilcox

Department of Mechanical Engineering, University of Bristol, University Walk, Bristol, UK

ARTICLE INFO

Article history:
Available online 20 August 2008

Keywords:
Phased array
Non-destructive evaluation
Post-processing
Ultrasonic imaging
Scanning

ABSTRACT

This paper describes a number of array post-processing methods developed for scanning applications in non-destructive evaluation. The approach is to capture and process the full matrix of all transmit–receive time-domain signals from the array. Post-processing the data in this way enables a multitude of imaging modalities to be implemented, including many that could not feasibly be achieved using conventional parallel firing techniques. The authors have previously published work on imaging algorithms for improving the characterisation of defects in solids by post-processing the data from a static linear ultrasonic array. These algorithms are extended and applied to data from a scanned array. This allows the effective aperture and range of probing angles to be increased, hence improving imaging and defect characterisation performance. Practical implementation issues such as scanning speed and data transfer are discussed.

1. Background

Ultrasonic arrays for non-destructive evaluation (NDE) are now routinely used in industry due to the flexibility that they provide [1–5]. However, they are often simply used as a replacement for one or more conventional monolithic transducers with their set-up and operation designed to emulate an existing testing procedure. Current array controller systems are designed with this in mind and are set-up to fire multiple elements with programmable time-delays between them so that the physical wavefront injected into the test-piece is equivalent to that from a monolithic transmitter. The received signals from elements in the array are typically recorded in parallel and then summed with appropriate time-delays to emulate the operation of an appropriate monolithic receiver. However, there is an increasing amount of work being carried out to investigate the improved use of arrays for non-destructive evaluation applications using, for example, inverse wave field extrapolation from the seismic field [6], synthetic aperture focusing from the sonar and medical fields [7,8] and super-resolution techniques developed for radar [9].

The majority of arrays currently used for NDE are one-dimensional (1-D) and consist of a row of rectangular elements as shown in Fig. 1. Throughout this paper the Cartesian co-ordinate system shown in this figure will be used. Here the array lies in the x–y plane and the normal or axial direction is parallel to the z-axis and a two-dimensional (2-D) image is produced in the x–z plane. The elements are relatively long in the y-direction, behaving approximately as infinitely long strip sources. 2-D arrays are also available [10,11] but although they have found use in medical applications, have yet to be fully exploited for NDE. These arrays tend to have square elements in a grid pattern and are used to image in three dimensions. As an alternative, 1.5-D arrays have been used in NDE to reduce the numbers of elements relative to a fully populated 2-D array [12].

There has also been significant development of ultrasonic array materials over the last 10 years. Recent developments have seen have seen an increase in the use of piezocomposite materials [13], which are particularly useful in the manufacture of flexible arrays [14,15] to allow testing of components with complex geometries [16].

In a static position a 1-D array can be used to produce linear swept B-scans or angular sweeps (Sector-scans) by firing a subset of elements, termed the aperture. By mechanically scanning the array in the y-direction, it is therefore possible to produce 3-D volumetric images of a component or C-scan images with a single pass. This type of array C-scanning is used in the aerospace industry [17], where there is a need to inspect large areas and in which the array offers a significant reduction in inspection time.

The work in this paper is focused on the use of 1-D arrays to scan parallel to the x-axis to increase the effective aperture and range of probing angles of the array. Section 2 of the paper describes an alternative to the standard method of array operation [1], which is based on obtaining raw time-domain signals from all permutations of transmitter and receiver elements in the array and performing beam forming in post-processing. Section 3

* Corresponding author. Tel.: +44 117 9289749; fax: +44 117 9294423.
E-mail address: b.drinkwater@bristol.ac.uk (B.W. Drinkwater).

0041-624X/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.ultras.2008.07.019

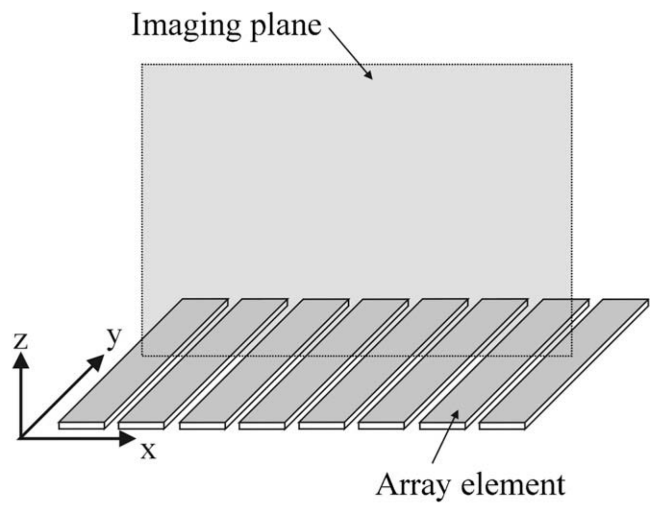

Fig. 1. Definition of array geometry for 1-D array.

describes the implementation of the algorithms for scanned arrays and finally Section 4 shows a number experimental results obtained and discusses the practical limitations of the FMC approach.

2. Full matrix capture and post-processing methods

In order to maximise the flexibility of array signal processing, as much information as possible should be extracted from an array. The complete data set from an n element array has a finite size and is an $n \times n$ matrix of time-domain signals from every possible transmitter–receiver element combination. This is referred to as the full matrix and the procedure for obtaining it is referred to as full matrix capture (FMC). In fact, it is possible to capture only $n/2(n+1)$ time-domain signals due to the reciprocity of pitch–catch signals and this is termed the half matrix. All possible processing algorithms, including those obtainable via conventional array operation may be implemented by post-processing the full matrix, together with an almost unlimited host of others. If the performance of FMC is compared to that of parallel transmission, it has been shown that although the signal to coherent noise ratio is identical, in the case of incoherent noise (e.g. electrical noise, ambient acoustic noise) the signal to noise performance of FMC is worse by a factor of $\sqrt{n}$ [18]. This is a potential drawback of FMC but it should be noted that it is rare for signal to incoherent noise to be a limiting factor in NDE, as it can be improved as required by averaging.

A schematic diagram of the data acquisition system is shown in Fig. 2. The system comprises a commercial array controller (manufactured by Peak NDT Ltd., UK) which contains 64 parallel transmission channels and is capable of FMC using 16-bit digitisation. A data acquisition interface written for Matlab (The Mathworks Inc., USA) is used to control the system and capture data using a 100baseT Ethernet connection. For the purposes of mechanical scanning, a rotary encoder is used to measure the position of the array and trigger the firing of the elements. The position of the array can be controlled manually or automatically with an *xyz* scanning frame.

A 32 element linear array with 5 MHz centre frequency (manufactured by Imasonic, France) was used with element dimensions 15×0.53 mm and the spacing between elements was 0.1 mm resulting in an element pitch of 0.63 mm. At the centre frequency of 5 MHz the wavelength of bulk longitudinal waves in aluminium is 1.26 mm, hence the element pitch is half the wavelength and grating lobes are suppressed.

2.1. Total focusing method (TFM)

One possible imaging algorithm that can only be performed practically by using FMC and post-processing is the total focusing method (TFM). This is a post-processing technique which uses all elements in the array to focus at every point in the image. The TFM yields a scalar image, in which the array is focused in transmission and reception at every point in the field of view. A detailed description of the method can be found in Ref. [1] so only the final equations are shown here. Consider a data set, $g_{(i)j}(t)$, of analytic time-domain signals (i.e. Hilbert transforms of the experimentally obtained time-domain signals containing real and imaginary components in quadrature) from one or more array positions on the same test-piece. The subscripts i and j refer to the indices of the transmitter and receiver locations, respectively (for the specific case of a data set from an array at one fixed position, these indices correspond to element indices in the array). Note that parentheses around a subscript indicate that the subscript is referring to a transmitter. The vector notation describing spatial positions is shown schematically in Fig. 3 for a 1-D linear array. The geometry is generalised such that the same imaging equations emerge for both static and scanned arrays. Let $\mathbf{r}$ denote the position vector of a point in the output image, $\mathbf{e}_{(i)}$ be the position vector of the ith transmitter and $\mathbf{e}_j$ be the position vector of the jth receiver.

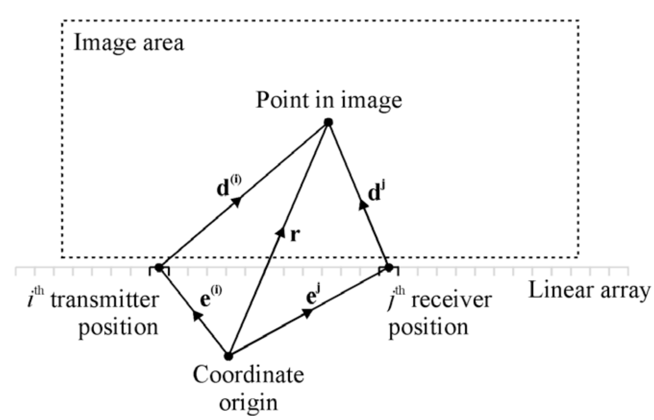

Fig. 3. Schematic diagram illustrating vector notation.

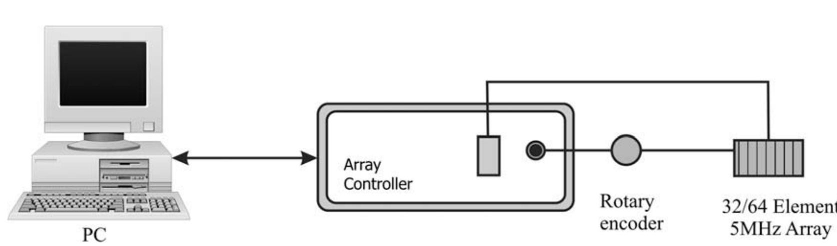

Fig. 2. Schematic of data acquisition system.