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Detection and Location of Internal Defects in Pieces by using Perpendicular Ultrasonic Apertures

Miguel A. Rodríguez[a],*, Antonio Ramos[b], José L. San Emeterio[b]

[a]Instituto ITACA, Univ. Politécnica Valencia, Camino Vera s/n, 46022 Valencia, Spain
[b]Instituto de Acústica, CSIC, Serrano 144, 28006 Madrid, Spain

Abstract

Ultrasonic inspection with a low number of transducers located in perpendicular planes, and working in near-field conditions, constitutes a recent evaluation tool with efficient behaviour for defect detection, because this option involves a low technological cost with a good spatial resolution. Each bi-dimensional elemental area of the tested piece is insonified by different transducers, and a high resolution two-dimensional representation can be obtained by using some digital signal processing techniques specifically developed for making echo-trace combinations. Two methods for acquisition of multiple A-scan lines, and three digital signal processing combination algorithms, together with some results related to the detections of multiple defects, are presented in the paper.

Keywords: digital signal processing; perpendicular insonification; transduction system; ultrasonic signals; echo-trace combination.

1. Introduction

Ultrasonic inspection systems capable to achieve high spatial resolutions of the tested pieces are very useful for numerous applications [1]. These systems usually need a high number of ultrasonic transducers to obtain the desired spatial resolution [2-4]. Recently, some alternative systems using a low number of transducers, that permit to obtain high spatial resolution, have been proposed [5]. These new and alternative systems are based on the use of transducers that perform the inspection from different planes, obtaining different views of the tested pieces. Combining these different types of information, a two-dimensional (2-D) representation of the scanned pieces, with high spatial resolution, can be obtained, only using a low number of testing transducers.

A type of such inspection systems, capable to achieve high spatial resolutions by using only eighth piezoelectric transducers, is described in this paper. These systems permit the generation of 2-D representations of pieces by

* Corresponding author. Tel.: +34963879309; fax: +34963879309.
E-mail address: marodrig@upvnet.upv.es.

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inspecting them from perpendicular planes with a very limited number of measurements. The ultrasonic scanning is performed with a set of transducers working in near field conditions and distributed over two ultrasonic arrays. All the transducers emit independently, in a sequential way, and a set of ultrasonic echo-traces is acquired. The A-scans lines, so collected by all transducers, must be combined by properly using some digital signal processing techniques, in order to generate a 2-D representation of the inspected area.

The acquisition procedures developed for it vary with the number of transducers that are receiving echoes in response to each ultrasonic shot. The transducers number is related to the shape of the searched defect or flaw; a simple defect can be detected and located correctly with only one receiving transducer at each ultrasonic shot, whereas a more complex defect needs the information of various receiving transducers for being evaluated. Several data acquisition procedures have been developed by the authors for our detection purposes; two of them are described in this paper, including some related graphical and mathematical results. In particular, the cases of reception with only one transducer and with three transducers are presented here; in addition, some inspection results using these two procedures are analyzed.

The particular signal processing algorithms, developed for traces combination, depend on the data acquisition procedure being used. The first objective of the combination is to obtain a 2-D representation of the inspected area. A second objective is attained at the same time: a reduction of the noise included in ultrasonic traces. The signal-to-noise ratio (SNR) of the resulting 2-D representation, after processing, is superior to the SNR of the acquired traces. For improving SNR, several digital signal processing tools have been utilized in echoes combination: techniques based on Hilbert, Wigner Vile [6] and wavelet [7-8] transforms, are applied along the paper.

The performance of this type of inspections is illustrated for different cases; the results obtained by using distinct acquisition procedures and several signals processing techniques for the combination, are also presented in the paper. All the inspections correspond to pieces with parallelipedic shape and containing different types of internal defects. Some graphic results, showing 2-D displays of inner parts in the inspected pieces, will be discussed.

2. System with perpendicular transducers and acquisition methods

A special signal detection arrangement for the acquisition of ultrasonic echo-traces from two planes is described in this paragraph. Based on this ultrasonic system, two different and complementary measurement methods have been developed. These methods have been designed and adapted to detect two kinds of defects in the materials under inspection.

Two arrays of transducers are the basis of the testing system, being each array formed by a low number of square piezoelectric elements of similar characteristics. The arrays are located on perpendicular insonification planes, so that each zone of the piece being inspected is insonified by two elemental transducers, one from each array. This system acquires at less two complementary measures from the perpendicular apertures, for each evaluated elemental zone.

Arrays forming the ultrasonic system can be similar or different, but at this time we are working with the same characteristics for both arrays and for all the transducers. In all cases, the transducers are operated in pulse-echo mode and radiate in near field conditions. Relatively collimated beams are obtained due to the near-field conditions of the rectangular shaped transducers, so that each transducer only insonifies a rectangular prism of the inspected piece, determined by the projection of the transducer emission surface. The final result is that every point of the inspected area in the piece is insonified by two transducers, one from vertical array and other from horizontal one, and at different times. The information for each point obtained in this double inspection process must be combined to obtain the final 2-D representation.

The above described transduction system can be employed with two alternative data acquisition methods. The first one has been designed for the inspection of pieces with small isolated flaws, while the second is recommended to detect more complicated defects.

In the two methods, all the transducers emit a pulse sequentially at certain repetition rate, and the reception of the echoes produced by the piece reflectors is done in each shot. The reception of the piece echoes can be performed by one or various transducers in each shot; the number of receptors considered determines the acquisition method. In method A, only the same transducer that emits the pulse (see figure 1) is used as a receiver of echoes, but in method

B, several transducers acquire ultrasonic echo-traces in each shot of one of them. In figure 1, transducer H4 emits and receives information from the "black point" and, in other time, transducer V2 performs the same inspection.

In method 1, the number of acquired A-scans is the same than the number of transducers of the system. For instance, if the system is formed by two arrays of N elements, the number of A-scan acquired by the ultrasonic system is 2*N. Then, it is necessary to combine 2*N traces to obtain the 2-D representation.

In method B, the number of acquired A-scans for each piece depends on the number of array transducers and on the total number of transducer receiving echoes in each shot. In this work, the number of receiving transducers per shot is reduced to three, for this second method (see figure 2): the emitting transducer and the two adjacent ones. Thus, if each array contains N elements, the number of acquired traces is 3*2*N - 4; the term "-4" corresponds to the 4 transducers at the ends of the arrays which only have one adjacent transducer. For instance, in the situation of figure 2, transducer H4 emits, and only H4 and H3 receive.

The different number of traces acquired by the two described methods implies two different level of complexity, both for acquisition procedure and for defect characterization capacity. Method A needs a low level of complexity in the acquisition procedure and in the combination algorithm but its detection capacity is limited to very simple defects as isolated flaws not very close among them. Method B implies a higher complexity in acquisition and combination than method A, but the performance in detection and location of difficult defects is better. Some results using methods A and B, with different type of defects, can be observed in figures 3 to 7.

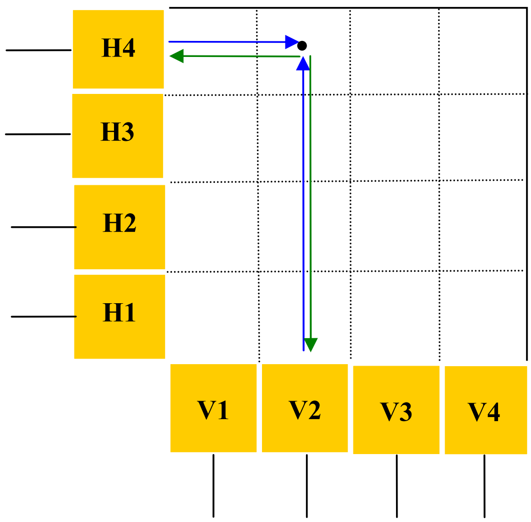

Fig.1 Schematic beam paths during the shots of transducers V2 and H4 for the inspection of a discontinuity (indicated by a "black point"), when using method A.

3. Digital signal processing algorithms for combination of ultrasonic traces

The two data acquisition methods, that have previously been described, have a specific combination technique associated to them. The number and the type of traces to be combined are related to the method utilised during the acquisition. Thus, for example, the number of A-scans to combine using an acquisition system with two arrays of 4 elements is 8 (2x4) if method A has been chosen and 20 (3x2x4 -4) in case of using method B.

Jointly with the data acquisition procedure, the second option that defines the digital signal processing algorithm is the support tool during combination. Three basic tools have been used in this work: the Hilbert transform, the wavelet transform and the Wigner-Vile transform. For acquisition method A, results using the three digital signal processing tools are displayed in the following (see figures 3 to 5), whereas representations for method B can be only obtained using Hilbert and wavelet transform, since Wigner-Ville transform presents some limitations when a lot of echoes appear due his non-linearity property [6].

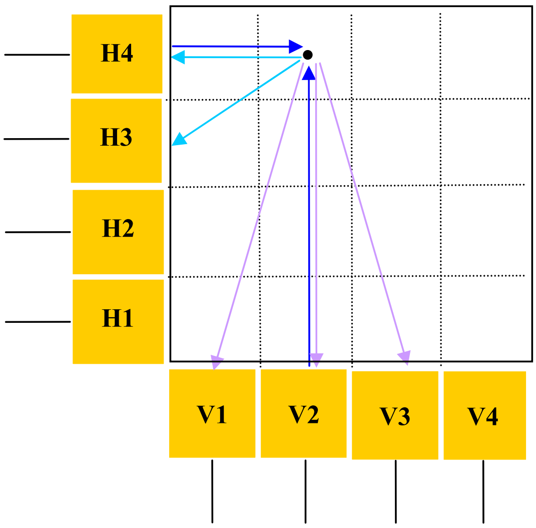

Fig.2 Schematic beam paths during the shots of transducers V2 and H4 for the inspection of a discontinuity (indicated by a "black point"), when using method B.

Combination methods provide two improvements in the acquired ultrasonic traces: the first one is that a high resolution 2-D representation can be obtained with a low number of A-scans lines measured with perpendicular ultrasonic apertures, but an additional improvement appears too, related to the final SNR. The SNR of the resulting 2-D representations is better than the SNR of the A-scans registers utilised for the generation of the 2-D display.

To quantify this SNR improvement, we define the SNR of the initial ultrasonic traces to be combined, SNR_{ini}, and the SNR of the resulting 2-D representation, SNR_{2D}.

It is possible to predict, by means of mathematical expressions, the SNR_{2D} from the values of the SNR_{ini}. For acquisition method A, authors have developed expressions for SNR improvements, corresponding to different signal processing tools for fussing the traces.

The Hilbert transform method is the most straightforward to implement but the SNR improvements are smaller than in the other two methods. In all cases, the value of SNR_{2D} is at least the double of SNR_{ini} , being the value of SNR expressed in dB.

$$SNR_{2DHilbert}(dB) = 2 \cdot SNR_{ini}(dB) \tag{1}$$

Wavelet transform method uses, in the combination process, different frequency bands of the initial A-scan. The quality of the final 2-D representation is higher than in Hilbert transform case, but the implementation complexity is higher too. The resulting SNR_{2D} in wavelet case is $SNR_{2DHilbert}$ multiplied by the number of frequency bands, L, utilised during combination [9]:

$$SNR_{2DWavelet}(dB) = L \cdot SNR_{2DHilbert}\ (dB) = 2 \cdot L \cdot SNR_{ini}\ (dB) \tag{2}$$

The Wigner-Vile based technique is the alternative with highest performance in SNR optimization. Different frequency bands are involved during fusion of traces like in the wavelet algorithm, but due to nonlinearity property of Wigner-Vile transform, the application of this tool is limited to detection of single defects. Although it is not possible to calculate the exact expression of SNR_{2DWVT} due to the nonlinearity involved, a good approximation is the following, which also shows that this option is superior to other 2 techniques in this aspect [10].

$$SNR_{2DWVT}(dB) \cong 3 \cdot L \cdot SNR_{ini} \ \ (dB) \tag{3}$$

The number of points of the 2-D representation determines the resolution. The pixels number of the 2-D representation .is related to the number of relevant samples, S, contained in each trace. For instance, in the case of 8 transducers, 8*S relevant samples are acquired using method A, and the resulting 2-D representation contains S^2 pixels

4. Simulations and results

Two benchmarks have been designed to test the two-plane ultrasonic system with the two acquisition methods. In both experiments, the inspection of a 24x24 mm square area of the inspected piece is considered for simulation. The ultrasonic system is formed by two perpendicular arrays containing four transducers each one, being the distribution similar to that shown in figures 1 and 2. Arrays are made up of square transducers working in near field conditions and driven in a sequential way. In the first experiment, a piece with a single hole is simulated. In this simple case, the detection and location can be done using acquisition method A.

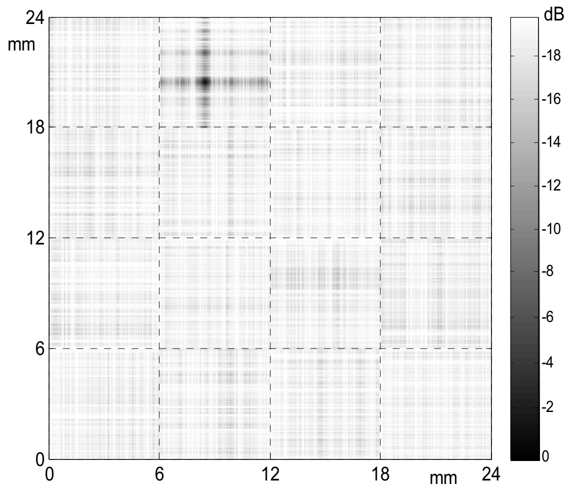

Fig.3 2-D representation of a square section of the inspected piece with a single hole, obtained by using the acquisition method A and Hilbert transform combination technique. SNR_{ini} = 12 dB, measured $SNR_{2DHilbert}$ = 23,87 dB.

It is assumed that the material microstructure of the inspected piece generates grain noise that makes difficult the detection and location of the defects. The size of the transducer elements in the two arrays (6x6 mm), as well as their central frequency -4 MHz-, agree with the parameters of an experimental prototype available in our laboratories. The sampling frequency used during the data acquisition is 128 MHz and the propagation speed in the material has been fixed to 2690 m/s. The hole inside the piece has been located at a distance of 8 mm in horizontal and 20 mm in vertical from the left down corner, in a position close to the reflector plotted in figure 1. Thus in this experiment using acquisition method A, where only one transducer receives information in each shot, the transducers H4 and V2 receive the echo coming from the defect, whereas the traces acquired by the rest of transducers (H1, H2, H3, V1, V3 and V4) contain only noise. The ultrasonic echo from the hole is positioned in the traces acquired by the transducers H4 and V2 considering the location of the defect, the propagation speed of the material and the sampling frequency.

The noise used is the addition of two components: the first corresponds to the grain noise, whereas the second is additive white Gaussian noise. The percentages over the total noise power are 50 % in both cases. Traces acquired by transducer H4 and V2 are formed by the hole echo plus noise, whereas traces of the rest of transducers (H1, H2, H3, V1, V3 and V4) only contain noise. The A-scans obtained by the eight transducers were simulated with a SNR_{ini} of 12 dB.

Of the three digital signal processing techniques for trace combination utilised, Wavelet transform was considered with two frequency bands and Wigner-Vile transform was used with three frequency bands. Figures 3 to 5 show the 2-D representations obtained for the three methods: Hilbert (figure 3), Wavelet (figure 4) and Wigner-Vile (figure 5). In these figures, it is possible to observe the high quality 2-D representations of the inspected area obtained by means of the combination of only 8 ultrasonic traces. The SNR_{ini} utilised in this experiment is 8 dB.

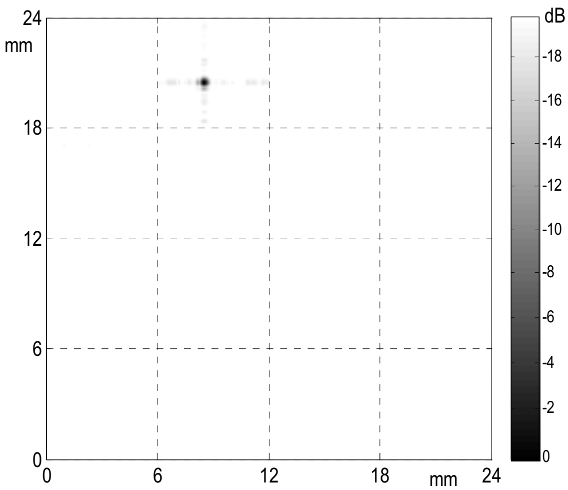

Fig.4 2-D representation of a square section of the inspected piece with a single hole, obtained using the acquisition method A and wavelet transform combination technique with 2 frequency bands. SNR_{ini} = 12 dB, measured $SNR_{2Dwavelet}$ = 47,58 dB.

Using the expressions (1) to (3), the expected SNR_{2D} are:

$SNR_{2DHilbert}$ = 24 dB, $SNR_{2Dwavelet}$ = 48 dB, SNR_{2DWVT} = 108 dB.

And the measured SNR_{2D} from figures 3 to 5 are:

$SNR_{2DHilbert}$ = 23,87 dB, $SNR_{2Dwavelet}$ = 47,58 dB, SNR_{2DWVT} = 117,22 dB.

A second 24x24 mm square area of other piece has been simulated with several defects. In this case, the piece contains nine holes forming a letter L. To difficult the inspection [11], the letter L was rotated, thus all the straight lines of the letter present an angle of 45 degrees respecting to any of the two inspection planes. The A-scan lines acquired by the transducers are considered noise free in this experiment. Two simulation tests were realised; in the first, with acquisition method A (only one transducer is receiving) and Hilbert transform combination.

Figure 6 show the results after combination. In this figure, we can observe 20 points: 9 corresponding to the searched holes and the other 11 phantom marks due to the limitations of this combination technique. Thus, figure 6 displays the discrimination problems appearing in this case with the acquisition method A.

The second test of the piece with 9 holes forming the letter L, was done using the acquisition method B. In this case, three ultrasonic traces were acquired in each shot; the transducers working as receivers are that emitting the ultrasonic pulse together with their two adjacent ones. Three A-scans are acquired in each shot (two, in the case of the transducers located in the borders of the arrays), that are necessary to make a more efficient trace combination.

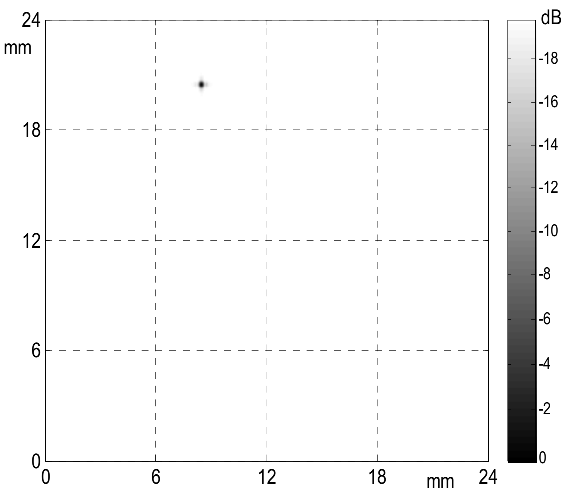

Fig.5 2-D representation of a square section of the inspected piece with a single hole, obtained by using the acquisition method A and Wigner-Vile transform combination technique with 3 frequency bands. SNR_{ini} = 12 dB, measured SNR_{2DWVT} = 117,22 dB.

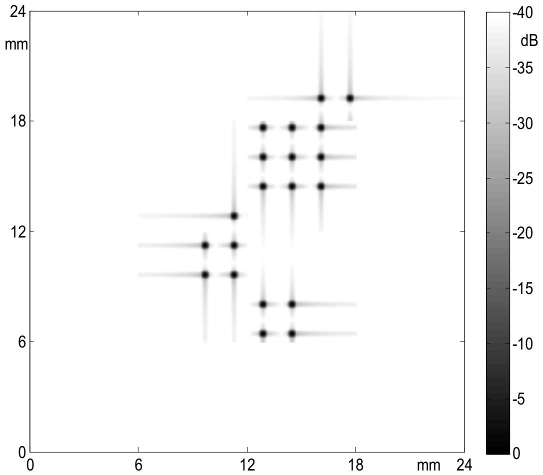

Fig.6 2-D representation of a square section of the inspected piece with 9 holes forming a letter L, obtained using the acquisition method A and Hilbert transform combination technique. Several "phantom" marks appear in this case.

Figure 7 displays the 2-D representation of the square inspected area of the piece, after its inspection by using the Hilbert transform combination technique. It can be observed the 9 marks that correspond with the 9 holes of the letter L. Comparing with figure 6, it can be noted that the 11 phantom marks have almost disappeared. Furthermore, the figure 6 marks are associated to some shadows, while the points of figure 7 are quite clear.

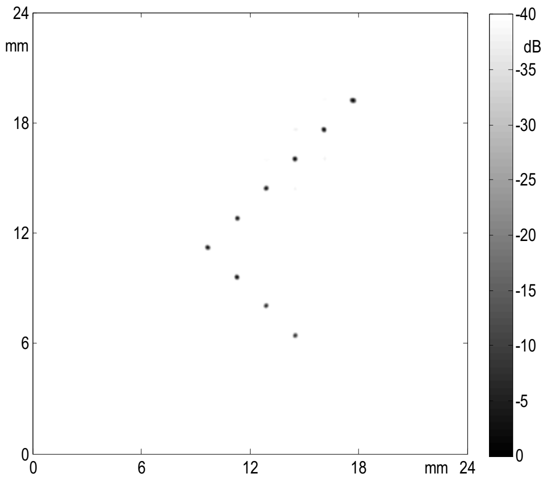

Fig.7 2-D representation of a square section of the inspected piece with 9 holes forming a letter L obtained using the acquisition method B (3 transducers are receiving in each shot) and Hilbert transform combination technique.

5. Conclusions

A two-aperture ultrasonic system for defect location has been presented in this work. It is based on two array transducers located at perpendicular planes. Two acquisition methods (A&B) have been described together with their associated digital signal processing techniques for the combination of the different A-scans acquired by all the transducers. The system produces 2-D representations of quality, by using only a reduced number of ultrasonic transducers (eight). Mathematical and simulation results have been included to show the performance of the system. Results obtained for a piece with one simple defect in noising environment were displayed for B option and three trace combinations. And results in a more complicate case (a set of small reflectors forming a L character shape), are included, with 2-D representations showing a good performance of the type-B acquisition method.

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