

# **SPATIAL COMBINATION OF TIME-DOMAIN SIGNALS DETECTED BY A TRANSDUCER SYSTEM FORMED BY PERPENDICULAR APERTURES**

PACS REFERENCE: 43.35, 07.05, 84.40

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## **ABSTRACT**

A novel ultrasonic signal combination technique intended for applying in detection systems based on multiple transducers is presented. The technique uses a spatial combination approach that considers the specimen inspection from several apertures located in different planes. Information received from transducers is fused in a common integrated pattern. The proposed method improves the detection of echoes buried in noise. A high quality image of the inspected material is obtained. Although the technique is valid for any kind of noise, the case of gaussian noise is treated with detail.

## **1. INTRODUCTION**

The inspection of materials from different positions with transducer systems composed by several elements is a technique utilized in the last years. Although it seems obvious that the information obtained from several traces must be greater than the obtained from a single one, the representation of this information is a problem without a standard solution. The methods for information fusion have proven useful for solving several problems using linear array signal processing techniques [1], but the techniques are under research when the traces come from different planes.

In pulse-echo ultrasonic non-destructive testing a broadband acoustic pulse is transmitted into the material and reflected echo signals are received with the same transducer. Each transducer covers a part ("line") of the inspected material, thus to test the whole piece is necessary to use array transducers or to move the same one. Pieces has different shapes with more than one surface, thus the inspection from different positions incorporates additional information to the test. The traces combination method depends on the concrete specimen shape and the geometrical positions of the transducers. This paper deals with rectangular specimens and perpendicular apertures.

Digital signal processing techniques are used for traces combination. First, the common information contained in different traces is selected. After, the ultrasonic signals are combined using mathematical operators. Several operators can be used, but in this work the product of the ultrasonic trace envelopes is utilized. The combination is obtained multiplying the information from the different perpendicular transducers. This method produces goods results with a low computational cost. The

last part of the algorithm consists on the image post-processing in order to minimize the residual noise.

The product combination technique assumes that if the material contains defect (discontinuity), two ultrasonic echoes will appear in the two perpendicular apertures, whereas if the material is defect free, grain noise will be detected and this will be uncorrelated for the two perpendicular apertures. The combination improves the signal to noise ratio of traces and obtains a high quality image of the inspected materials with a small number of transducers. In section 3 an example is presented where inputs are 8 A-scans (Figure 2) with 200 points and the resulting image (Figure 3) has a resolution of 40.000 pixels (200x200).

Another important aspect is that during combination process the statistics of the grain noise change. The design of optimal detectors implies the characterization of these statistics [2]. With the statistics of the noise after combination and assuming a model for the ultrasonic echo pulse, the design of a detector that maximizes the signal to noise relation can be done [2]. In this paper the particular case of gaussian noises is addressed and the analytical expression of the probability density function of the noise after the product is obtained. This result is one of the contributions of the paper.

## 2. TRACE ENHANCEMENT BY MEANS OF PRODUCT COMBINATION

In pulse-echo ultrasonic testing a pulse is emitted and a delayed echo is expected if defect exist. But in any case the material response introduces grain noise, which difficult the echo detection. To quantify the relative influence of noise in echo detection the signal to noise ratio is defined:

$$\frac{S_1}{N_1}(dB) = 10 \log \frac{\frac{1}{M} \sum_{i=1}^M (pulse(i))^2}{\frac{1}{L} \sum_{i=1}^L (noise(i))^2} \quad (1)$$

where *pulse* denotes the echo pulse and *noise* represents the grain noise, *M* is the length of pulse and *L* is the length of the ultrasonic trace.

For combination two linear operator has been studied: sum and product, resulting the improvement of product greater than the sum one. Applying the product operator, two possibilities appear: first, if defect exist, the pulse envelope is multiplied by itself and second, if material is defect free, the new noise is obtained by the product of the noise envelopes. The signal to noise ratio after fusion is:

$$\frac{S_2}{N_2}(dB) = 10 \log \frac{\frac{1}{M} \sum_{i=1}^M (pulse(i))^2}{\frac{1}{L} \sum_{i=1}^L (noise(i))^2} \cdot \frac{\frac{1}{M} \sum_{j=1}^M (pulse(j))^2}{\frac{1}{L} \sum_{j=1}^L (noise(j))^2} = 10 \log \left( \frac{\frac{1}{M} \sum_{i=1}^M (pulse(i))^2}{\frac{1}{L} \sum_{i=1}^L (noise(i))^2} \right)^2 \quad (2)$$

Comparing (1) and (2):

$$\frac{S_2}{N_2}(dB) = 2 \cdot \frac{S_1}{N_1}(dB) \quad (3)$$

The conclusion is that if the combination is carried out by means of the envelopes product, the signal to noise ratio is improved by a factor of 2.

## Noise product characterization

To reduce the noise in the combined image interesting information is the statistical distribution of the resulting noise. With this information a specific detector can be designed for the echo pulse [2]. The characterization depends on the statistics of the ultrasonic grain noise. In the next paragraph the case of gaussian noise is solved.

Let be  $a$  and  $u$  the envelopes of two Gaussian noises modelled by a random variable with Rayleigh probability density functions expressed by:

$$\begin{aligned} p_1(a) &= a \cdot e^{-\frac{a^2}{2}} \\ p_2(u) &= u \cdot e^{-\frac{u^2}{2}} \end{aligned} \quad (4)$$

We multiply the random variables  $a$  and  $u$  obtaining a new random variable  $c$  expressed by:

$$c = a \cdot u \quad (5)$$

It is known [3] that if  $a$  and  $u$  are two random variables independents and positives, the probability density function of their product  $c$  will be obtained by the expression:

$$p(c) = \int_0^{\infty} p_1(a) p_2\left(\frac{c}{a}\right) \frac{1}{a} \cdot da \quad (6)$$

Replacing (4) in (6):

$$p(c) = \int_0^{\infty} a \cdot e^{-\frac{a^2}{2}} \cdot \frac{c}{a} \cdot e^{-\frac{-(c/a)^2}{2}} \cdot a \cdot da = \int_0^{\infty} a \cdot e^{-\frac{1}{2}(a^2 + \frac{c^2}{a^2})} c \cdot da \quad (7)$$

Changing the variable  $h = a^2$  and reorganizing:

$$p(c) = \frac{c}{2} \cdot \int_0^{\infty} \frac{1}{h} \cdot e^{-\frac{1}{2}(h + \frac{c^2}{h})} dh \quad (8)$$

The above expression is equivalent to [4]:

$$p(c) = c \cdot K_0(c) \quad (9)$$

where  $K_0(c)$  is the modified Bessel function of third kind and order 0

Now, we can compare the expression (9) with the probability density function of the K-distribution [5]

$$p(c_1) = \frac{2b}{\Gamma(m)} \left( \frac{bc_1}{2} \right)^m K_{m-1}(bc_1) \quad (10)$$

where  $c_1$  is the random variable,  $b$  and  $m$  are the parameters of the distribution (being  $m_e$  greater than 0),  $K_{m-1}$  is the  $(m-1)$ -th order modified Bessel function of third kind and  $\Gamma(m)$  is the gamma function

Selecting the parameter  $m$  to 1 (the parameter  $b$  is just a scale factor equal to  $2\sqrt{m}$  when the noise is unit power normalized)

$$p(c_1) = \frac{2b}{\Gamma(1)} \left( \frac{bc_1}{2} \right)^1 K_0(bc_1) \quad (11)$$

Replacing  $b$  by 2 and  $\Gamma(1)$  by 1, expression (11) results:

$$p(c_1) = 2 \cdot 2c_1 \cdot K_0(2c_1) \quad (12)$$

Comparing expressions (9) and (12) we can observe that the two random variables have equivalent probability density functions. The difference is a power normalization factor.

From the above demonstration, the conclusion is the product of the envelopes of two independent gaussian noises follows a K-distribution with parameter  $m$  equal to 1.

### 3. EXPERIMENTAL RESULTS

To test the combination method performance, a simulated arrangement with a piece of rectangular cross-section containing two ideal reflectors inside has been selected. Eight transducers, divided in four horizontal (H1, H2, H3 and H4) and four vertical (V1, V2, V3 and V4), have been distributed around the piece (Figure 1). One reflector affects to transducers H2 and V3 and the other affects to H4 and V2.

The ultrasonic echoes from the reflectors have been generated using a real echo pulse from a Krautkramer MSW-QC5 5 MHz transducer sampled at 16 MHz. The grain noise has been simulated by mean of additive gaussian noise. Figure 2 shows the simulated ultrasonic traces for the eight transducers with a signal to noise ratio of 3 dB. The length of the traces is 200 points.

After the traces combination, by using the product operator, the result is the image of the inspected material shown in Figure 3a. This image has a resolution of 40.000 (200X200) pixels. Finally the signal to noise ratio of this image is improved by means of a digital signal post-processing based on the statistical characterization of the section 2. Figure 3b shows the image after signal processing where the noise of Figure 3a has been reduced.

Some parameters have been measured. The K-distribution of grain noise after fusion has been confirmed by means of the Raghavan test [6] resulting a parameter  $m$  of 0.98. The signal to noise ratio before combination is 3 dB and after the combination is 5.99 dB.

Several experiments with different number of transducers, different geometrical defect positions, different signal to noise ratios, and different echo signals have been done confirming the results presented in this paper.

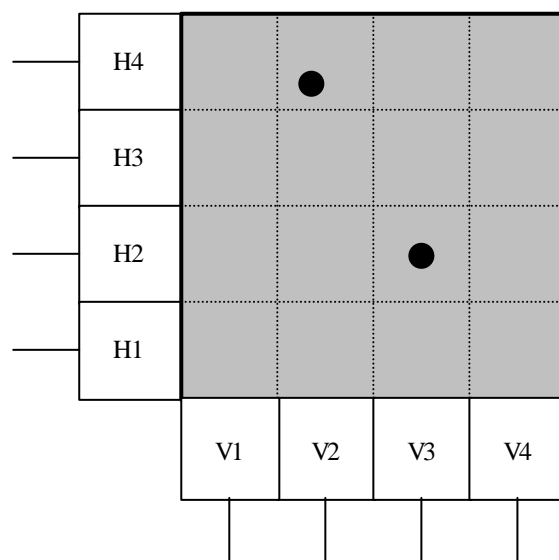


Figure 1. Scheme of the proposed experiment.

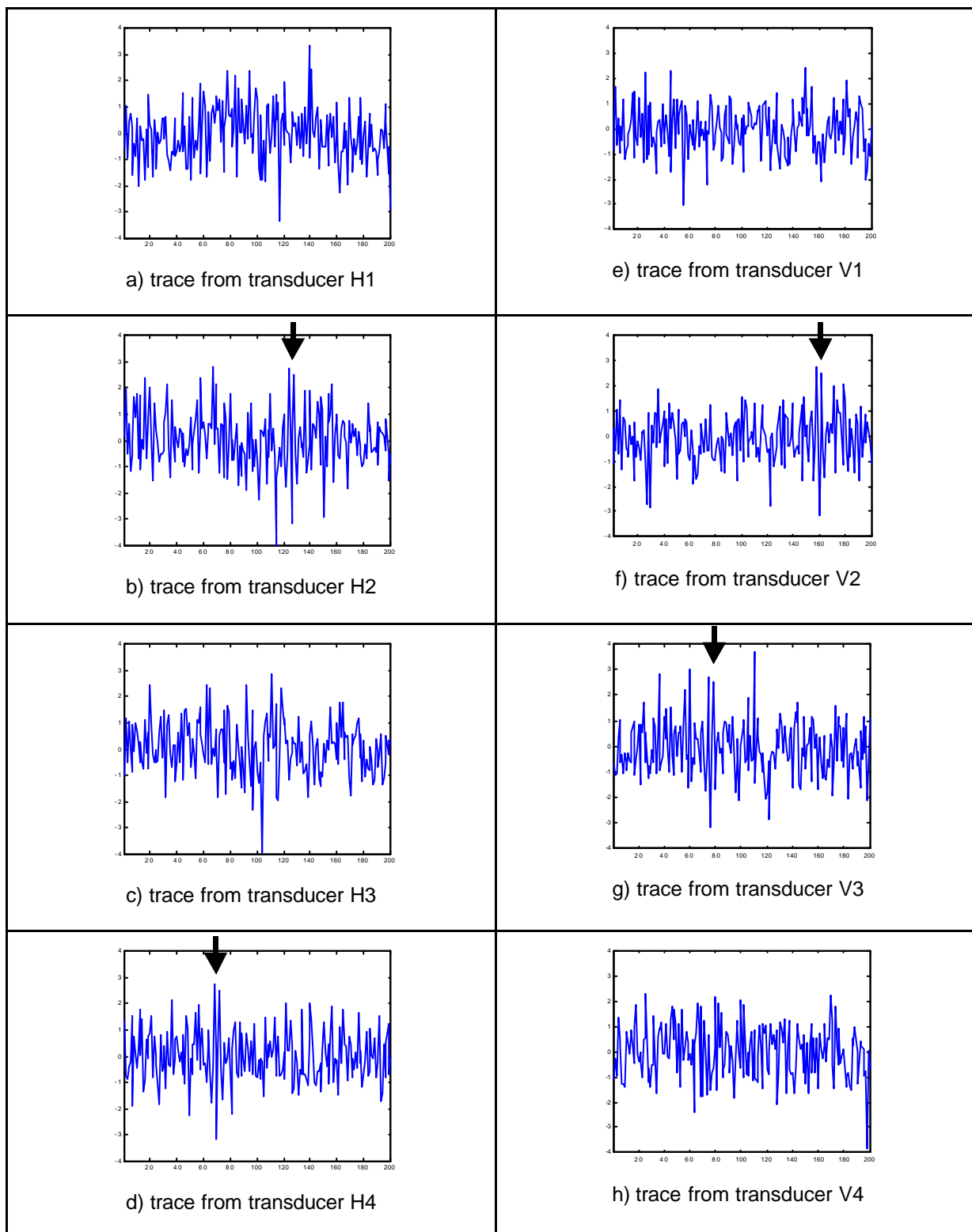


Figure 2. Synthetic ultrasonic traces from the proposed experiment. Figures a), b), c) and d) correspond to the horizontal transducers and figures e), f), g), and h) to the vertical ones. In figures b), d), f) and g) the ultrasonic echoes from defects are marked with arrows.

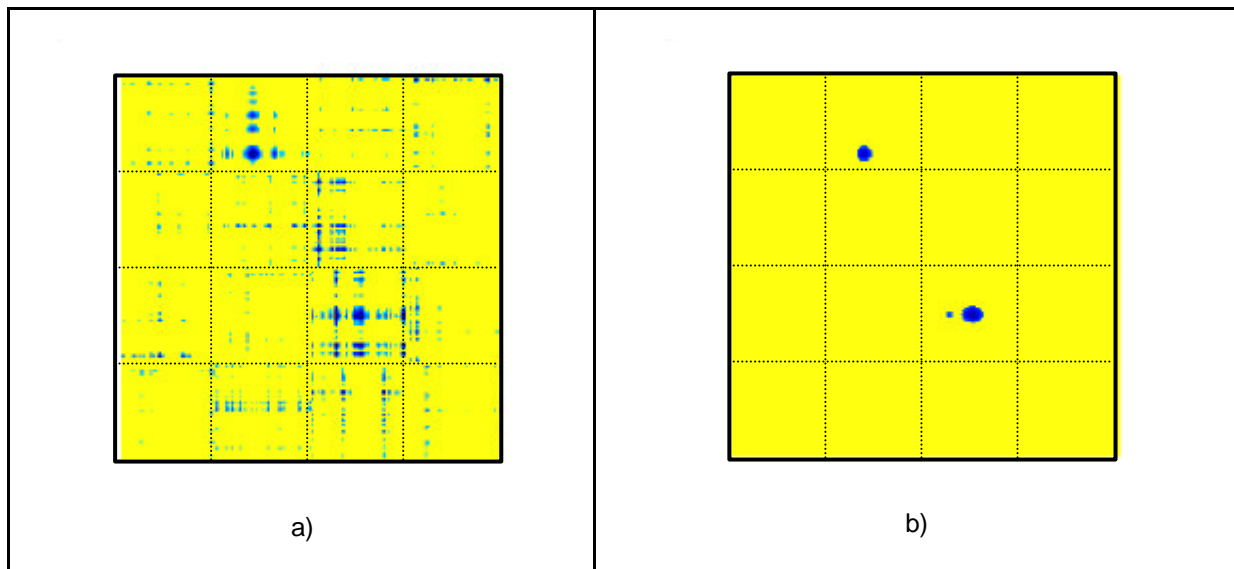


Figure 3. Results: a) image after combination and b) image after signal processing for noise reduction.

#### 4. CONCLUSIONS

A novel technique for signal combination has been presented. The method improves the signal to noise ratio of ultrasonic Ascans by a factor of 2. The algorithm utilized for the combination is the product of the trace envelopes. The result is an ultrasonic image with high resolution. The envelope product combination case with gaussian noise has been studied with detail in the paper. The analytical statistical characterization of the product of two gaussian noises is another contribution of the paper. An illustrative experiment is presented in the last part of the paper.

**Acknowledgments:** The work described in this paper has been supported by the Spanish R&D Project C.I.C.Y.T. - Ref. TAP99-0864.

#### REFERENCES

- 1. H. Krim and M. Viberg, "Two decades of Array Signal Processing Research". IEEE Signal Processing Magazine, Vol. 13, pp. 67-94, July 1996.
- 2. H.V. Poor, "An introduction to Signal Detection and Estimation", Springer-Verlag 1994
- 3. P.L. Meyer, "Introductory Probability and Statistical Application", Addison-Wesley 1970
- 4. G.N. Watson, "A treatise on the theory of Bessel functions", Cambridge University Press, 1952.
- 5. E. Jakeman and P.N. Pusey, "A Model for Non-Rayleigh Sea Echo", IEEE Trans. on Antennas and Propagation, Vol. AP-24 pp. 806-814, November 1976.
- 6. R.S. Raghavan, "A Method for Estimating Parameters of K-Distributed Clutter", IEEE Trans. on Aerospace and Electronic System, Vol. 27 pp. 238-246, March 1991.