ENVELOPE-BEAMFORMER LOCATION OF INHOMOGENEITIES

L. Medina[+], **and E. Moreno**[*]
+DISCA-IIMAS, Universidad Nacional Autónoma de México, D.F. MÉXICO
[*] ICIMAF, La Habana, CUBA
lucia@uxdea4.iimas.unam.mx

Abstract

An innovative approach to locate inhomogeneities in a propagation medium is presented. An algorithm has been developed to implement SAFT for an ultrasonic pulse-echo system. This method is based on the time-of-flight measurement of echo signals and process the information with a time-domain beamformer applied to the envelope of the received signals, avoiding the increment on side lobe amplitude when the distance between two adjacent transducer's positions is larger than λ/2. This digital process produces a matrix with entries representing the energy system. Maximal elements of the matrix represent the spatial location of in-homogeneities. Resulting matrices were calculated for several distances between two neighboring transducer positions, reducing the computational operations. The resulting image, for each distance, is not affected in its longitudinal resolution, however in its lateral resolution becomes poorer when the distance of two consecutives receiver location is larger than 1.5λ.

Introduction

Ultrasonic B-scan imaging has been successfully used in medical diagnosis, nondestructive testing and underwater imaging. Currently, the most popular method to obtain an image is the pulse-echo method. Pulse echo measurements made at several transmitter/receiver locations with a wide beam transducer produce a map of ultrasonic reflectivity enhancing lateral and longitudinal resolutions of the resulting image [1]. To reconstruct the ultrasonic image and to locate the regions of maximal reflectivity, a time-domain beamformer has been developed. The beamformer proposed by the authors relies on the time-shifts applied to the envelope of the signals diminishing the side lobe amplitude of the radiation pattern and also the distance between any two transducer's position can be greater than λ/2 (λ wavelength), drastically reducing the computational time.

Theory

A pulse-echo ultrasonic imaging system consists of transmitted and receiving a pulse or train of pulses through the propagation medium either by using a single mechanically operated transducer or an array.

When the transmitted ultrasonic pulse or train of pulses encounters a specimen with different acoustic impedance respect to the propagation medium, an echo is produced and detected by the transducer or transducers.

Each received signal is digitally processed to obtain the information inherent in them, such as the time of flight given by:

$$\tau_n = 2\frac{r_n}{c} \tag{1}$$

where r_n the distance between the *nth*-transducer and the specimen, and c is the speed of sound in propagation medium. If a single fixed transducer is used, the only information about the specimen location is whether or not it is within the visible region of the transducer. Therefore additional measurements must been carried out either by moving the transducer through and specific path or by using an array of sensors. To determine the angular position of the specimen, a further analysis is needed, such as beam-forming technique [2]. This method uses the appropriate delay to the received signals to achieve focusing and, the direction of arrival of the energy onto the transducer or the array of sensors being determined.

Envelope Beamformer Technique

Webb [3] proposed a modified algorithm of the classical time-delay beam-former for a pick-and-place robot operation. This modified algorithm applied the time delays, on reception mode, to the envelope of the received signal. The detected envelopes are considered to be very sharp and having a length of about 3 to 5 cycles and the receivers are very narrow slits with a λ/2 width. The main advantage of the envelope beamformer is that the inter-element distance between any two adjacent array elements can be larger than λ/2 without the generation of grating lobes. Also the time processing and computational operations are significantly reduced.

The time-delay beam-former output, $B(t)$ is given by

$$B(t) = \sum_{n=1}^{N} w_n s_n\left(t - \Delta t_{F_n}\right) \tag{2}$$

where w_n is the *nth*-amplitude weight, $s_n(\cdot)$ is the *nth*-received signal, Δt_{F_n} is the time delay required to steer the beam to an specific direction, and N is the total number of received signals.

The steering time delay can be defined as

$$\Delta t_{F_n} = 2\frac{\sqrt{\left(y_F - y_n\right)^2 + z_F^2}}{c} \qquad (3)$$

where y_F and z_F is the focal point coordinates, and y_n is the transducer position, respectively (see Figure 1).

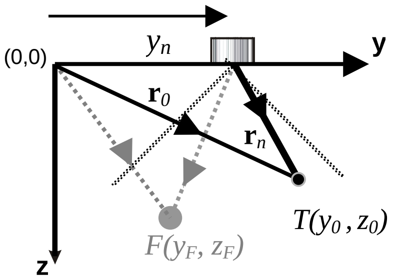

Figure 1: 2D geometry: *F* is the focal point and *T* is the target position

Methodology

A mechanically moved single transducer, which produces a wide beam of ultrasound, is used to transmit and received echoes. The received signals are envelope detected via the Hilbert transform, the weights are considered to be unity, and the time delay for each focusing point is calculated by eq. (3).

The envelope time-domain beam-former, for 2D in-homogeneities location, consists of the following steps [4]:

a) The region of interest is represented as a net of LxP nodes (L lines with P pixels per line), the number of lines depends on the lateral distance covered by the scanning process, and the total number of pixel per line is given by length of the received signals.

b) The beam is digitally steered pixel by pixel. At each focusing point the geometrical distances between the *nth*-transducer position and the focusing point, must be calculated and the round trip distances computed, considering the visible region of the transducer.

c) The round-trip distances are translated into number of samples.

d) The envelope of the signals are evaluated and summed at those specific samples.

The output of this digital process is an LxP matrix, containing the points at which the received signals are added constructively and destructively. The maximum amplitudes must coincide with the in-homogeneity location in the region of interest.

Experimental Setup

The experimental work was carried out with a Hydrophone scanning system (Specialty Engineering Associates SEA, CA, USA), two Personal computers (Pentium II, 128 RAM), a digital oscilloscope (TDS-340 Tektronix, Oregon, USA), a narrow slit Toshiba (Toshiba Corporation, Japan) ultrasonic transducer, which produces a 1.25 MHz pulse, and a pulse-eco card MATEC SR9000 (Matec Instrument Companies, MA, USA) to control de triggering of the ultrasonic pulse.

The ultrasonic transducer and the phantom were immersed in a water tank, the transducer was mechanically moved by the motor system, and the corresponding signal was recorded and stored.

The phantom consists of two acrylic cylindrical pipes of 6mm diameter and 11 mm length (see Figure 2).

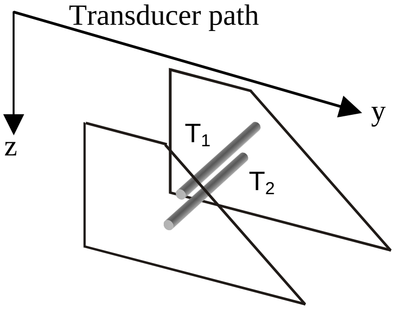

Figure 2: Phantom immersed in a water tank, that consist of two acrylic pipes at $T_1(y_1, z_1)$, and $T_2(y_1, z_2)$.

Results

The ultrasonic transducer moves in the *y*-direction and transmits and receives ultrasonic signals at a constant spatial interval, $d_y \cong \lambda/2$. The pulse repetition is about 0.2 ms, the total number of samples for each firing is 500 covering 150 mm on *z*-direction, the sampling rate is f_s=2.5 MHz (the Nyquist frequency), and 0.6 mm as a range resolution. The number of lines and pixels are 117 and 500, respectively.

Figure 3 shows the reflectivity map produced by the received signals. In this image three arcs and a hyper-intense stripe can be observed, where the stripe represents the echo coming from the water tank bottom. Because of the T_2 position respect to T_1, the arcs marked with T_2 in Figure 3, represents a single pipe. From this image, the location of the pipes cannot be precise. For that matter the envelope beamforming algorithm must be applied to the reflected signals.

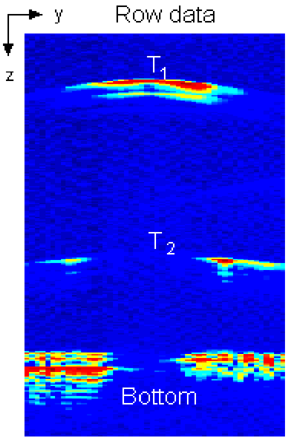

Figure 3: Reflectivity images formed with received signals at different transducer positions (y).

The beam-former steered the beam as follows: $0 \leq y_F \leq 70$ mm and $r_r \leq z_F \leq 150$ mm, at a 0.6 mm step.

The first result of the time-delay beam-former is shown in Figure 4, and it was obtained including the echoes produced by the bottom of the water tank, where all the signals are in phase, their intensity amplitude is considerably larger than the echoes from the phantom pipes.

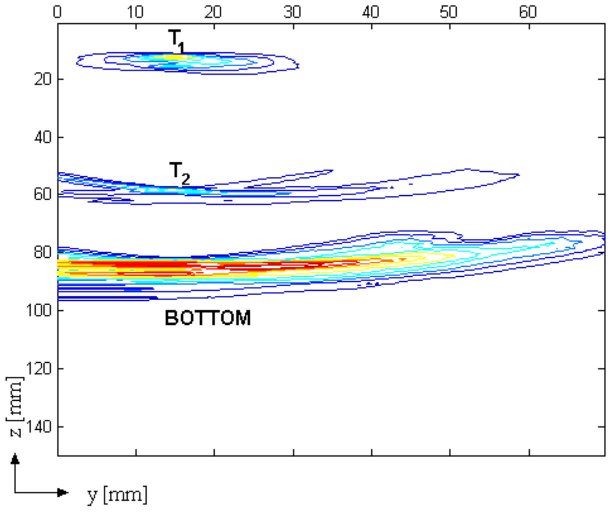

Figure 4: Contour of the beamformer output

A second process was developed at which the echoes coming from the bottom were neglected. The resulting image (see Figure 5) allows the location of the pipes to be determined. The two peaks, in the image, correspond to in-homogeneities in the scanned medium. Their maximum amplitude location, within *yz*-plane, is approximated to the pipes position and the error is within the range resolution of the system given by 0.6 mm.

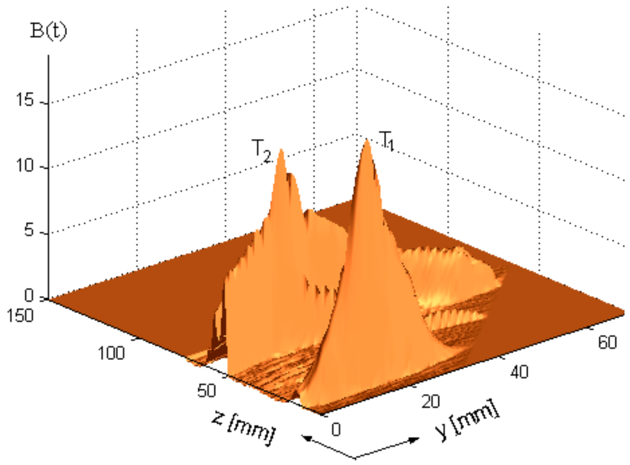

Figure 5: 3D image of the resulting beamformer matrix.

Figure 6a shows the image of the detected pipe-phantom T_1. The only information from this image is that an in-homogeneity is present in the region of interest.

Figures 6b to 6f show the beamformer output when d_y is varied from 0.5λ to 2.5λ. These images consist of a single point of maximum amplitude at the same *z*-position. However, for a distance larger than λ, the lateral resolution becomes poorer (see Table 1).

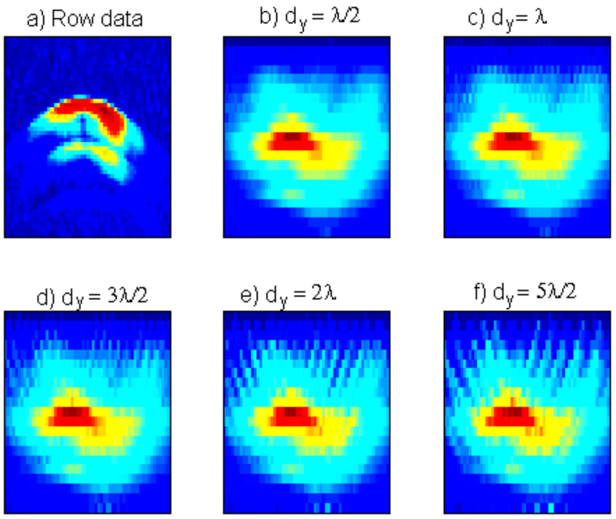

Figure 6: a) Detected flaw T_1, and b-f) d_y is varied from $\lambda/2$ to 2.5λ, respectively.

Table 1: In-homogeneity location T_1 as a function of distance between adjacent transducer's positions

d_y [λ]	y [mm]	z [mm]
1/2	13.8	12.0
1	13.8	12.0
3/2	14.4	12.0
2	13.8	12.0
5/2	15.6	12.0

The pipe named T_2, has been detected as two different regions, as shown in Figure 7a. The reason for this behavior is due to the position of T_2 respect to T_1 that one is just under the other. Then the transducer is not able to detect T_2 at a normal distance from it.

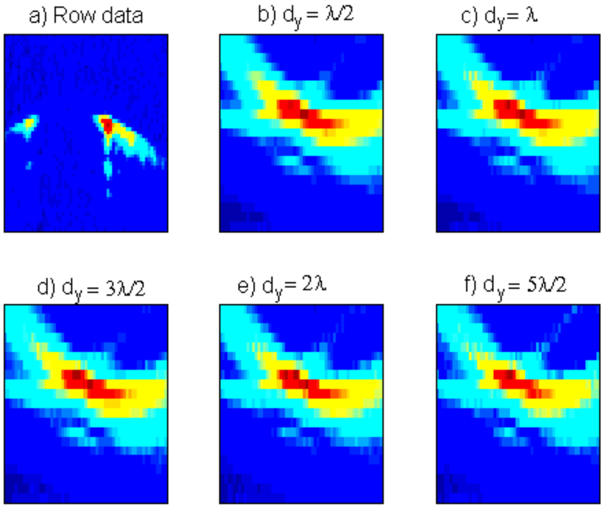

Figure 7: a) Detected flaw T_2, and b-f) d_y is varied from $\lambda/2$ to 2.5λ, respectively.

The image in figure 7b shows the beamformer output, when d_y=0.5λ. It represents a single in-homogeneity with a maximum value at (18.6, 58.8), this *y*-value does not correspond to the real T_2 lateral position, which has to be close to 13.8 mm. A different analysis must been carried out in order to decrease the error. Figure 7c to Figure 7f show how the images are pixeling when d_y increases. However as in the T_1 location, the longitudinal resolution is not altered because of this increment as summarized in Table 2.

Table 2: In-homogeneity location T_2 as a function of distance between adjacent transducer's positions

d_y [λ]	y [mm]	z [mm]
1/2	18.6	58.8
1	18.6	58.8
3/2	18.6	58.8
2	16.2	58.2
5/2	16.2	58.2

Conclusions

A time-domain envelope beam-former applied to ultrasonic signals, transmitted and detected by a wide beam ultrasonic transducer to scan a 2D region, has been presented. The resolution of the in-homogeneities location is within the range resolution for distances, between two adjacent transducer positions, smaller than 1.5λ. This means that the error between the real position of the in-homogeneities and one obtained with the digital process is around ±0.6 mm.

Results considering distance between two adjacent transducer positions, greater than λ/2, had been reported. When the distances between two neighboring transducer positions are varied, the longitudinal resolution is almost constant. However, the larger the distance is the poorer the lateral resolution.

Further research must be done in order to increase the lateral resolution without decreasing the distance between two adjacent transducer positions.

The envelope beam-forming algorithm produces a high-resolution image and also the processing time and the number of computational operations can be drastically reduced without loosing information about the in-homogeneities location.

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