AIRBORNE ULTRASONIC RANGING SYSTEM: A COMPARISON BETWEEN BEAM-FORMING TECHNIQUES

REFERENCIA PACS: 43.28.Tc

Medina Lucía [1]; Sánchez Israel [1]; Wykes Catherine [2].
1 DISCA-IIMAS,UNAM;
Apdo. Postal 20-276 Admon. No. 20, México D. F., 01000,
Tel: 552 622 3623. Fax: 552 616 0176
E-Mail: lucia@uxdea4.iimas.unam.mx;
Apdo. Postal 20-276 Admon. No. 20, México D. F., 01000,
Tel: 552 622 3582. Fax: 552 616 0176
E-Mail: israel@uxdea4.iimas.unam.mx;
2 School of Mech., Mat., Manuf., Eng. and Manag., Notts. University
University Park, Nottingham NG7 2RD, U.K.
E-Mail: Catherine.Wykes@nottingham.ac.uk

ABSTRACT

Beamforming techniques have been used as 2D and 3D ranging methods in areas such as radar and sonar. The main disadvantage of these techniques is the requirement of $\lambda/2$ distance between transmitting/receiving elements to avoid ambiguities due to sidelobes in their radiation factor. This restriction can be overcome if short pulses are considered, and applying the beam-former process to the envelope of the receiving signals only. A comparison between continuous and envelope beam-forming techniques is presented. The comparison is made by varying the aperture length from 2 λ to 50 λ, considering filled and thinned array geometries. The beamforming outputs are calculated for each geometry. The results show that the larger the aperture the better the resolution, also the processing time increases when the number of receiving elements is high. However, if the beamforming process is applied to the envelope of the received signals of thinned arrays, produced with short pulses, the resolution will not be drastically affected, the processing time will be considerably reduced and the amplitude of sidelobes does not altered the beam-formation results. This work is based on the characteristics of the airborne ultrasonic transducer built at Nottingham University. Nevertheless, this method can be applied to any short pulse-echo ultrasonic system in which echoes are envelope detected.

INTRODUCTION

Airborne ultrasonic has been widely used for distance measurement, object recognition[1], obstacle avoidance[2] and robot guidance[3]. Also as a 2D[4,5] and 3D[6] ranging air-coupled systems.

Airborne ultrasound system based on pulse-eco technique have been used to detect the presence of a target within the beam pattern, providing range measurement. The direct information available from these systems is the time of flight (TOF) measurement, given by

$$t = \frac{2R}{c} \qquad (1)$$

where R is the range and c is the speed of sound in air.

To get the angular position of the reflectors, either the transducer must be mechanically moved or an array of sensors should be used. If an array of sensors is used, the angular position can be found from the received signals, applying beam-forming methods[7].

BEAMFORMING METHOD

The sensors outputs, delayed and amplitude weighted by an appropiate amounts and added together, reinforce the estimate of the amplitude of a coherent wavefront in the presence of the background noise and spatially localised interference This signal processing algorithm is known as delay-and-sum beamforming technique[7].

The delay-and-sum beam-former, in the time domain, output is given by

$$b(t) = \sum_{n=1}^{N} w_n y_n(t - \Delta t_n) \qquad (2)$$

where y_n is the *nth* output signal, its amplitude weight w_n, Δt is time delayed and N denotes the total number of receiver elements. The amplitude weights w_n are applied to achieve a desired spatial response of the receivers; if no mutual coupling between them is considered, then w_n is unity valued. The time delay, Δt_n, required to steer the array, electronically, to the specified direction ($\mathbf{k}_F$), is given by

$$\Delta t_n = \frac{\sqrt{|\mathbf{x}_n - \mathbf{x}_0|^2 - |\mathbf{R}_{F_n} - \mathbf{R}_F|^2}}{c} \qquad (3)$$

where R_F, R_{F_n} are the distance from the focal point to the point of reference and to the *nth* receiver element, respectively, $\mathbf{x}_n$ is the receiver element position with respect to the point of reference and c is the speed of sound in air. If the far field condition is assumed the received signal as a delayed version of the transmitted signal, y_n can be written as

$$y_n(t,\mathbf{k}) = A\exp^{jw_c(t-\Delta t_n)} = A\exp^{j(w_c t - \mathbf{k}\cdot\mathbf{x}_n)} \qquad (4)$$

where A, w_c and $\mathbf{k}$ are the wave's amplitude its angular frequency and its direction, respectively. The beam-former output $b(t)$ is then written as

$$b(t) = A\exp^{jw_c t}\sum_{n=0}^{N-1}\exp^{j(\mathbf{k}_F-\mathbf{k})\cdot\mathbf{x}_n} \qquad (5)$$

where

$$W(\mathbf{k}_F - \mathbf{k}) = \sum_{n=0}^{N-1}\exp^{j(\mathbf{k}_F-\mathbf{k})\cdot\mathbf{x}_n} \qquad (6)$$

is known as radiation factor of the array[8], which depends on the array geometry. Then, the beamformer output is

$$b(t) = W(\mathbf{k}_F - \mathbf{k})A\exp^{jw_c t} \qquad (7)$$

<u>Radiation Factor</u>

The radiation factor is a quantity which determines the amplitude and phase of the beamformed signal when the wavefield consists of a single plane wave, it also determines the ability of the array geometry to detect the direction of the maximum energy. If a continuous wave arrives to an N element linear array with elements equally spaced by a distance d with no coupling between them, the argument of the array factor, is given by

$$(\mathbf{k}_F - \mathbf{k})\cdot\mathbf{x}_n = n(kd(\sin J_F - \sin J)) = nq_G \qquad (8)$$

Where J_F and J are the focusing angle and angular direction of energy, respectively. Then $W(\mathbf{k}_F - \mathbf{k})$ can be written as

$$W(q_G) = \sum_{n=0}^{N-1} \exp^{jnq_G} = \frac{1}{N}\left[\frac{sin\left(N\dfrac{q_G}{2}\right)}{sin\left(\dfrac{q_G}{2}\right)}\right] \qquad (9)$$

which is a periodic function with maxima and minima values. Those values depend on the distance d and the aperture length Nd. The principal maxima are at $sin\,J_F = \pm 2\pi m sin\,J$, called grating lobes, the main lobe is at $sin\,J_F = sin\,J$, and secondary maxima, called side lobes or minor lobes, which are the lobes between maxima values. The sidelobe amplitudes depend on the number of elements and the distance between them. When the distance between elements is increased, the grating lobes and sidelobes increased as well. If grating lobes are to be avoided d must be less than l (wavelength) also if sidelobes amplitude must be diminished, N must be increased.

ENVELOPE BEAM-FORMING[5]

A new approach to beam-forming was developed by Webb (1994) in Nottingham, which filtered, delayed and summed the output signals of finite length. The signals which consists of a few cycles of the wave are envelope detected and can be approximated by

$$y(t) = \begin{cases} a(t)\cos wt & -\dfrac{t_s}{2} \le t \le \dfrac{t_s}{2} \\ 0 & otherwise \end{cases} \qquad (10)$$

where $a(t)$ is the envelope of the signal which amplitude modulated the function $\cos wt$. The total field received by the array, from the far field, is

$$E = \sum_{n=1}^{N} E_n = \sum_{n=1}^{N} y_n(t + \Delta t_n) \qquad (11)$$

which is not a periodic function as is the case of classical theory of continuous waves explained previously. The time delayed added to the nth signal in order to steer the array to certain direction is defined as

$$\Delta t_n = \frac{R_F \cos J_F - \sqrt{R_F^2 - 2R_F sin\,J_F x_n + x_n^2}}{c} \qquad (12)$$

The advantages of this technique compared to the classical beam-forming techniques are that the signals are added constructively only in one summation, as shown in Figure 1 and restriction on the inter-element distance disappear.

The main requirement of this technique is the width of the envelope must not be very wide and has to be sharp to enable the peak to be detected.

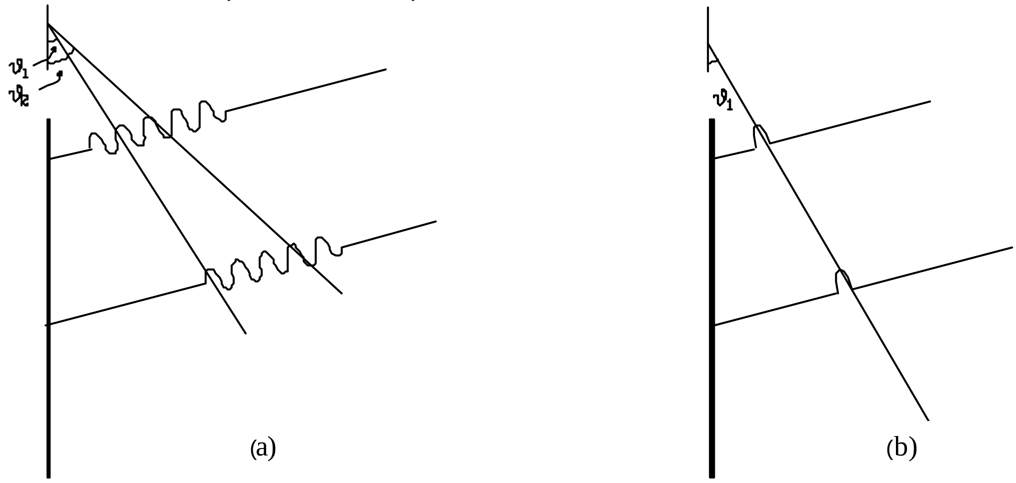

Figure 1 A comparison between (a) Continuous wave and (b) envelope beam-formers.

SIMULATION

The simulation of a pulse-eco system is based on the characteristics of the Nottingham transducer[9]. It uses a capacitive transducer with resonant frequency of 100kHz, bandwidth of 25kHz. The transmitter produces a pulse consisting of five pulses at the resonant frequency whose envelope is approximately Gaussian and the return signal from a point target has the same form.

The continuous wave simulation model considers a monochromatic wave with a resonant frequency of 100 KHz.

The aperture and the distance between receiving elements are varied as follows:

- The starting aperture is 2λ followed by 5λ until we reach 50λ with step of 5λ.
- The distance between elements varies from d= $\lambda/2$ (filled) until the distance given by a 30% thinned array, for each aperture length.

The radiation factor given by eq. (9) is calculated for each aperture and array geometry considering the CW case. For a pulse-eco system, for each array geometry, received signals are simulated and the envelope beamforming applied to them.

RESULTS

The simulation of continuous and pulse-eco systems were developed using MATLAB™. The starting array geometry for each aperture is filled array with inter-element distance of $\lambda/2$. The distance between element is increasing, therefore the number of element is decreasing for a fixed aperture length. Figure 2 sketches the radiation pattern and the envelope beamformer output of filled, and thinned arrays for a 2λ aperture length. Figure 3 and Figure 4 show how the sidelobes amplitude increases due to the inter-element distance is larger for a continuous wave case, while the envelope beamformer ouput is not drastically affected.

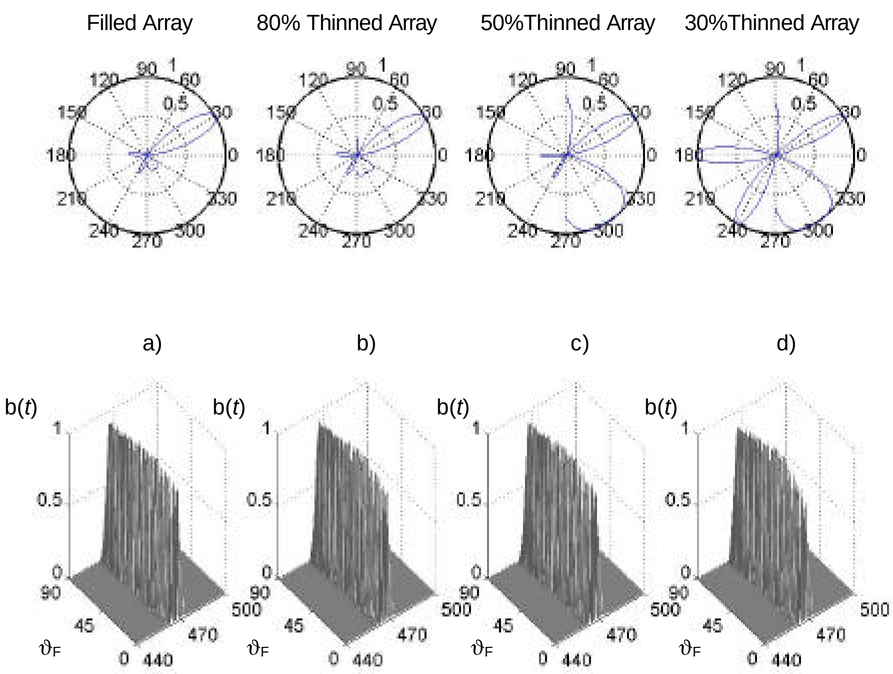

Figure 2. 2λ aperture length, a) d= $\lambda/2$, b) d=$2/3\lambda$, c) d= λ, and d) d=2λ.

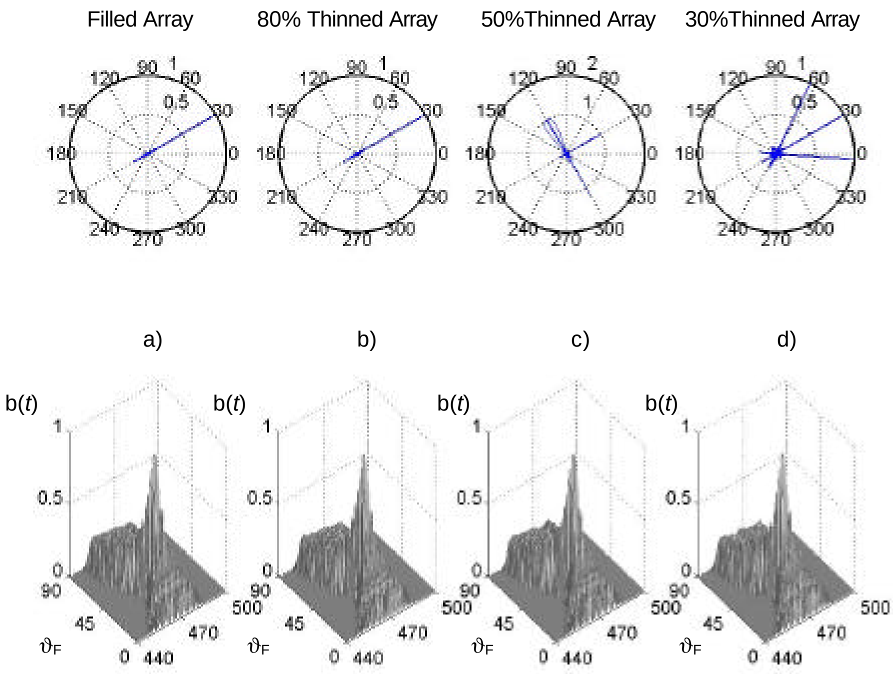

Figure3. 25 *l* aperture length, a) d= *l*/2, b) d=0.63 *l*, c) d= *l*, and d) d=1.79 *l*.

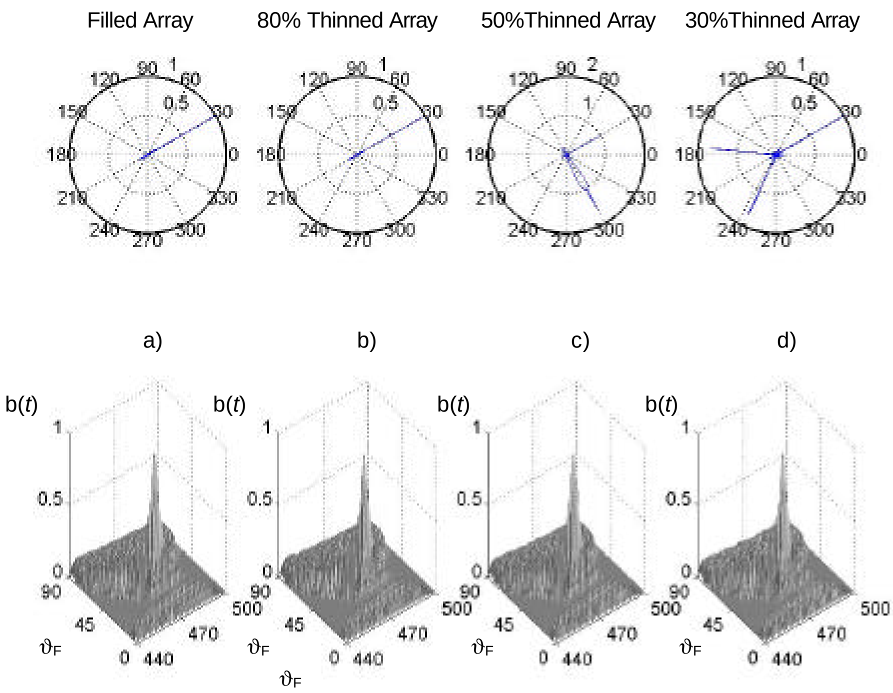

Figure 4. 50 *l* aperture length, a) d= *l*/2, b) d=0.63 *l*, c) d= *l*, and d) d=1.72 *l*.

CONCLUSION

A comparison between CW and envelope beamformers has been presented. The beamforming technique applied to the envelope of the received signals gives the following advantages, without affecting the resolution of the results:

a) the number of element in the array can be reduced.
b) the interelement distance is increased.
c) the processing time and data storaging are considerably decreased

REFERENCES

1. Lach M., Ermert H., “An Acoustic Sensor for Object Recognition”, Sensors and Actuators A, 25-27, pp. 541-547, 1991.
2. Borenstein J., Koren Y., “Obstacle Avoidance with Ultrasonic Sensors”, IEEE J. of Robotics and Automation 4, pp. 213-218, 1988.
3. Figueroa F., Mahajan A., “A Robust Navigation System for Autonomous Vehicles using Ultrasonics”, Control Eng. Practice 2, pp. 49-59, 1994.
4. Ullate L. G., Sánchez M. T., Villanueva E., Parrilla M., Anaya J. J., “A Three-transducer Ultrasonic System for Object Location in Air”, Sensor and Actuators A37-38, pp. 391-396, 1993.
5. Webb P. F., “An Ultrasonic based System for Extraction of Range and Bearing Data for Multiple Targets”, Ph. D. Thesis, Nottingham University, 1994.
6. Medina L., Wykes C., “Multiple Target 3D Location Airborne Ultrasonic System”, Ultrasonics (aceptado marzo 2000).
7. Mucci R. A., "A Comparison of Efficient Beamforming Algorithms", IEEE Trans. ASSP-32, pp. 548-558, 1984.
8. Johnson D. H., Dudgeon D. E., “Array Signal Processing: Concepts and Techniques”, Prentice-Hall, Inc., New Jersey, 1993.
9. Munro W.S.H., Wykes C., “Arrays for 100 kHz Airborne Ultrasound”, Ultrasonics 32, pp. Pp. 57-63, 1994.