Simulation of 2-D Linear Array Transducers and Beam Profile Used in Echolocation

Luminita MORARU*, Laura ONOSE*,, Ana – Maria CHISELEV***

**Dunărea de Jos University of Galaţi, Physics Department, str. Domneasca nr. 47, RO-800008 Galaţi, Romania, luminita.moraru@ugal.ro, anachiselev@yahoo.com*
*** Metallurgical High School, str. 1 Decembrie 1918 nr. 25, RO- 800511 Galaţi, Romania, laura.onose@yahoo.com*

Abstract: The reason for using sonar for mobile robot navigation comes from the ultrasonic sensing capabilities of bats which use echolocation to determine their prey position. During the project "Adaptive bio-mimetic sonar heads for autonomous vehicles" we intend to employ a new material to build up broadband ultrasonic transducers featuring good adaptation to air. In this specific case it is important to achieve accurate information about the magnitude and position of the peak pressure and intensity produced by the probe. The purpose of the simulation is to analyze the emitted beam pattern from 2D-array transducers in terms of the spatial impulse response that characterizes the three-dimensional extent of the ultrasonic field. Simulation results are provided for two different linear array element numbers to evaluate the effects on the beam profile.

Keywords: linear array, beam profile, simulation

1. INTRODUCTION

Many researchers have proposed ultrasonic sensor systems that bats use to capture their prey. Bats employ echolocation for prey capture by emitting a series of acoustic pulses and subsequently processing the resulting echoes. In the field of robot navigation, broadband air ultrasonic transmitters and receivers are important. Similar with bat species, the transducers are required to operate within a frequency range of 20 – 200 kHz (Helversen et all. 2006). This condition is met by a new transducer material, i.e. cellular polymer film called electro mechanical film (EMFi). EMFi is a polypropylene film of 30 – 70 µm thickness and cellular structure resulting from its manufacturing process (Bauer et al. 2004; Paajanen 2000; Reinhard et al. 2007). By means of such a transducer that features ultrasonic broadband with good adaptation to air, it is possible to achieve an extraordinary performance in ultrasound object recognition. The advantage of this new material arises from their good electromechanical coupling efficiency. This implies improved sensitivity and potential for bandwidth enhancement over existing transducers. This new material is yet to make an impression on the NDE marketplace and it will take some years before they are routinely used in array manufacture.

Arrays are used for imaging in applications ranging from medical ultrasound to sonar, seismic and radar. A wave field is emitted into a medium and, through scattering and reflection, an image can be formed from the received signals. The wave field energy can be focused in a specific direction, both at transmission and reception, through beam forming (Drinkwater and Wilcox 2006).

To avoid spatial aliasing, the placement of the array elements must satisfy the spatial sampling criterion. Depending on the pulse shape and the steering sector, the inter-element distance will for practical purposes lie between half a wavelength and one wavelength of the pulse centre frequency.

The primary reason for development the 2D array systems is that they allow for the design of systems that are capable of real-time formation of volumetric datasets due to their ability to perform beam steering in both elevation and azimuth.

Rao et all. (2008) described a frequency domain B-mode imaging model applicable for linear and phased array transducers. In their paper, the authors extend this model to incorporate 2D array transducers. The model is compared with the widely used ultrasound simulation program FIELD II, which utilizes an approximate form of the time domain impulse response function. A new method that, without applying any approximation, converts the two dimensional Rayleigh integral over the transducer surface to one dimensional integral expression is reported by Behnam and Tajvidi (2007). A lot of advanced studies were performed on 2D arrays focused on the array acoustic optimization. It was intended to manufacture sub-apertures of 2D array with 2.5 MHz center frequency, 64*64 active elements and 300µm pitch (Ratsimandresy et al. 2002; Ratsimandresy et al. 2005).

The aim of this work is to provide a coherent analysis of 2D linear array transducers design in terms of the spatial impulse response that characterizes the three-dimensional extent of the ultrasonic field for a particular transducer geometry. This analysis allows for the optimization of their design for a particular application, namely an EMFi ultrasonic transducer that emits an ultrasonic beam capable of scanning the environment for object localization. We should be able to change the transducer parameters and graphically show the beam pattern pressures produced by these transducers, in order to optimize the design of the array transducers for this particular application. The optimization criteria follow the creation of beam patterns with low main lobe width and low side lobes. The reason for studying 2D linear arrays in only one direction is that this is a small extension to the current manufacturing methods using EMFi technologies.

The main simulations are done for a set of linear array during the project "Adaptive bio-mimetic sonar heads for autonomous vehicles ADBIOSONAR" where the objective was to construct and study a mobile sonar bio-mimetic head that allow a very good exploration/navigation/orientation of the robots in small enclosed areas.

In our simulations we used FIELD II which is an interactive, menu-oriented simulator for finding the sound field from transducers. It is a tool for designing the transducer arrays and transducer geometry, and it increases the user's understanding of acoustic wave propagation through the spatial impulse response analysis. The simulator has primarily been developed for medical ultrasound, but has also been used for sonar analysis and non-destructive testing. The simulator has been developed over the last ten years and it is implemented as a freeware toolbox in MATLAB. Field II has been used and evaluated extensively in ultrasonic transducer modelling and has been validated by many researchers for accuracy (Jensen 1996; Jensen 2001).

The spatial impulse response gives the emitted ultrasound field at a specific point in space as function of time, when the transducer is excited by a Dirac delta function. The field for any kind of excitation can then be found by just convolving the spatial impulse response with the excitation function. The impulse response will vary as a function of position relative to the transducer, hence the name: spatial impulse response. 3D simulations were employed to verify pulse-echo response of the array configurations.

In trying to optimize the performance of arrays using as few elements as possible, it is desirable to find simple methods to implement this demand. A question that can be raised is whether an increased number of elements of the 2D-arrays can improve the performance of the array. One aim of this article is to show that flat 2D-arrays that have a small number of elements work properly in terms of spatial impulse response. Relationships between main and side lobes, the focal point and the number of elements will also be studied.

2. EXPERIMENTAL

The principle of phased array ultrasonic beam generation is based on the use of individual transducer elements that can each be independently driven with controlled phase delays of excitation. Using this phase delay, the ultrasonic beam parameters, such as focus depth and/or the beam angle can be varied while testing is being carried out. This results in an improved capability for mobile robots to navigate.

In many technical applications, the cost of the arrays is proportional to the number of elements. Often there are also technical difficulties in fitting a high number of elements and cables on the surface of a transducer. It is therefore desirable to reduce the number of elements without losing the imaging quality. This is a combinatorial optimization problem, and many papers have dealt with it for flat 2D-arrays. In the attempt to optimize the array performance with as few elements as possible, it is desirable to find easy methods to implement this procedure. The optimization criteria are: creation of beam patterns with low main lobe width and low side lobes. The linear arrays acquire a rectangular image, and the arrays can be quite large (often 128 or 256 elements) to cover a sufficient region of interest. Attenuation is neglected here to simplify the simulations and results analysis. Our simulations are based on the two apertures with 20 elements and 64 elements.

First we designed a 20- element elevation focus, a linear array with an elevation focus at 10 mm (Fig. 1) (Onose et al. 2009).

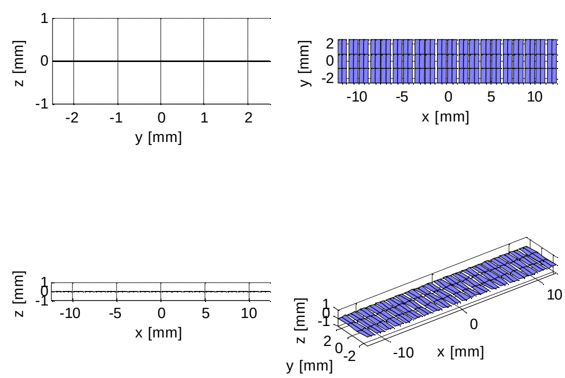


Fig. 1. 20 elements elevation focused linear array

The spatial impulse response for this aperture was calculated and plotted by time. Figure 2 shows the spatial impulse responses from a linear array with 20 elements for different spatial positions from the front face of the transducer. The responses are found from the centre of the rectangle and out in steps of 2 mm in the x direction to 10 mm away from the centre of the array. The impulse response is zero before the first wave reaches the aperture. When the edges of the aperture are met the response drops off. The decrease with time is steep, and the response becomes zero when the projected waves are all outside the aperture area.

Then, the signal received from these 20 scatterers, for each element in the aperture, was calculated. The individual responses and the summed response were plotted (Fig. 3). This simulation result is suited for showing the spatial variation of the point spread function for a particular transducer, focusing, and apodization scheme (Fig. 3a). Also, it can be seen how the spatial impulse response changes as a function of relative position to the aperture (or time variation) in Fig. 3b.

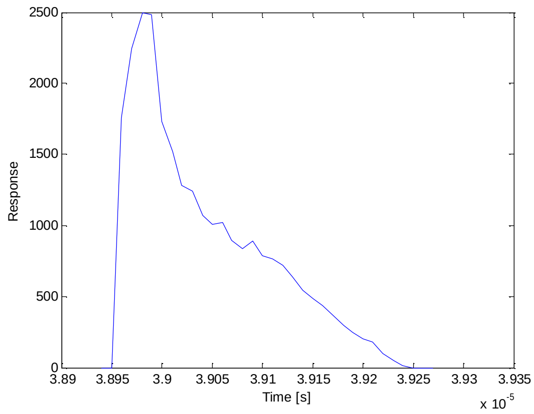
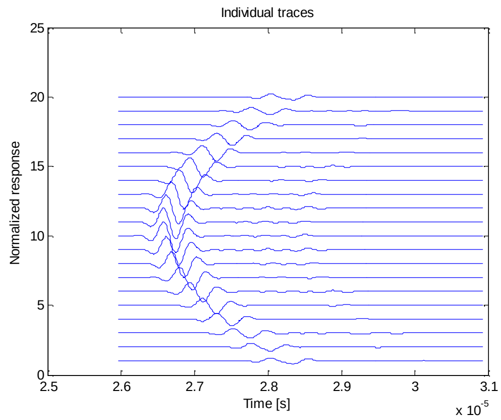
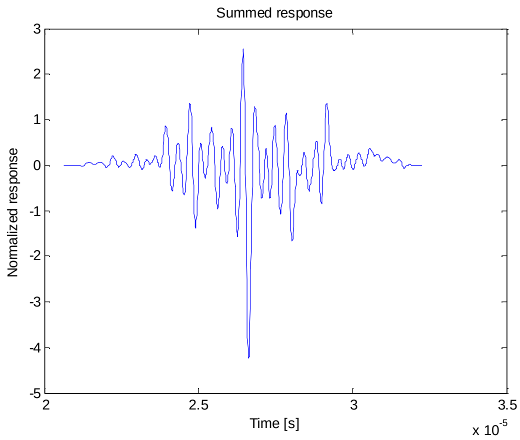


Fig. 2. Spatial impulse responses from 2D linear array with 20 elements



a)



b)

Fig. 3. (a) The individual responses and (b) the summed response, from 20 element linear array

The trace of the 20th element is illustrated in Figure 4. The impulse response is zero before the first wave reaches the aperture. When the first edge of element of the aperture is met the response drops off. The decrease with time is more pregnant, when the edges of the central elements of the aperture are reached.

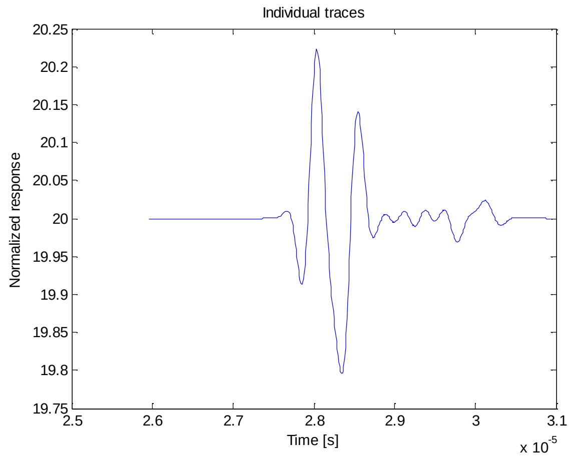


Fig. 4. The individual trace from 20th element of linear array

3. RESULTS AND DISCUSSION

The effective aperture size is an important parameter for 2D array systems since it determines the number of elements required for a given element size and spacing between adjacent elements. For bio-mimetic sonar application (namely the construction and study of sonar heads that are based on the shape and behaviour of real world creatures and that are far from similar performances used in nature, like the case of bats) it is desirable to use a small number of active elements to obtain good response. This small aperture must have very small dimensions, comparable with those of very small animals (bats). However, a small aperture emits a weak ultrasound signal. On the other hand, larger apertures provide an improved ultrasound resolution but introduce increased noise artifacts due to the narrower beam width. We need to take into consideration this trade off when choosing the aperture size of the 2D transducer array for bio-mimetic sonar. Therefore, it is useful to understand how the aperture size affects the signals.

Following our intention to use a new material EMFi to build up broadband ultrasonic transducers with good adaptation to air, it is important to achieve accurate information about the magnitude and position of the peak pressure and intensity produced by the probe. These goals could be achieve through appropriate design of the emitted beam pattern from 2D-array transducers in terms of the spatial impulse response that characterizes the three-dimensional extent of the ultrasonic field, for particular transducer geometry. Our purpose is to design an efficient bio-mimetic EMFi transducer using these simulation results.

Analyzing the spatial impulse responses and summed response we can design a beam former that is a spatial–temporal filter used to “look” in the direction of transmitted signal while eliminating interference, or jamming signals, which cannot be removed through temporal filtering or carrier demodulation alone. Our sensor arrays must collect spatial samples of a propagating wave and then beam formers are used to generate a weighted, phase-delayed summation of those samples (Fig. 3a). Adaptive beam forming techniques dynamically adjust the array pattern to optimize some characteristic of the received signal, i.e., signal strength, direction of received signal, etc. An array using adaptive beam formers can reject interfering signals having directions different from those of the desired signals. This desideratum is met by the individual trace of linear array (Fig. 4). The impulse response becomes zero when the projected waves are all outside the aperture area.

The aperture is defined as the active area of a transducer. For rectangle transducer shape, the beam is asymmetric along two dimensions. The aperture size and its width and length depend on which dimension we want to calculate the beam. For a linear array several elements work together. For 64 elements, the aperture size is 64 x element width (= kerf). We must noticed that pitch is the element width plus kerf size. Axial resolution is defined as half of pulse length. Lateral resolution is F_{number} x wavelength, where F_{number} is ratio of focal depth and aperture size. To achieve good axial resolution, short pulse is required. That is why broadband transducer is important.

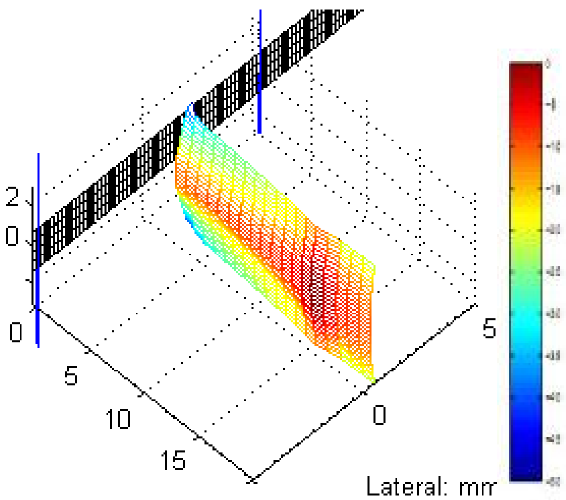


Fig. 5. Ultrasound beam profile simulation for linear array with 64 elements (by courtesy BioSono Inc.)

As an example of the ultrasound beam profile simulation in free 3D space, the full-field pressure is shown in Figures 5 and 6. The array is located on the X-Y plane, and the results of the acoustic field are shown in the X-Z plane and in X-Y&Y-Z&X-Z planes. These 3D simulations allow us better visualization of the ultrasound beam profile in order to adopt a viable solution to design a linear array able to scan the environment for object localization.

The transducer modelled is a linear array aperture with 64 elements, excitation in 50% bandwidth Gaussian Pulse, 5 MHz centre frequency and electric focus (Lateral Elevation Axial) at 15mm (Fig. 5).

The element dimensions are 0.2 mm width and 2 mm height and with 2 sub-element in lateral and 3 sub-element in elevation. For the purposes of the simulations the element kerf was assumed to be 25 µm. The parameters used in this simulation are summarized in Table I.

TABLE I. Parameters of the simulation

Start	Step	Stop	
2	1	20	Axial (mm)
-5	0.2	5	Lateral (mm)
-3	0.2	3	Elevation (mm)

The simulation domain was 5 cm laterally, 2 cm in elevation, and 20 cm in depth, on the positive quadrant of the lateral-elevation plane.

Figure 6 illustrates the results of the simulation for a linear array aperture with 20 elements accomplishes using the same parameters (Table I). The element dimensions are 0.2 mm width and 2 mm height and with 2 sub-element in lateral and 4 sub-element in elevation. Only the aperture size is changed in this second simulation.

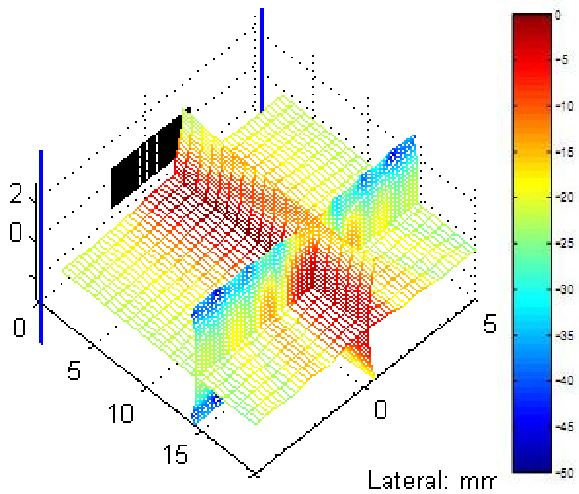


Fig. 6. Ultrasound beam profile simulation for linear array with 20 elements, in X-Y&Y-Z&X-Z planes (by courtesy BioSono Inc.).

In both simulations, the elevation and lateral side lobes present features that are less than 35 dB down from the peak or off axis with respect to the lateral and elevation planes.

By increasing the number of elements, the effective transducer diameter will increase so the main and side lobes and the distance of the maximum pressure point were increased. Existence of grating lobes shown in Fig. 5 is the effect of increasing this parameter.

Axial resolution increases with bandwidth, while lateral resolution decreases with bandwidth. The total response for the array system is the combined effect of the element response and the beam forming. Note that only the beam pattern is affected by the steering, the element response cannot be changed by beam forming.

4. CONCLUSION

This paper presents the simulation results which allow estimating the ultrasound field of 2D linear arrays with different elements number used for construction and study of transducers of the sonar head that are based on the form and behaviour of real world creatures, like the case of bats. The Field II method uses the exact calculation of the Rayleigh integral for a transducer element in an array and then, by proper result shifting, obtains the field of other transducer elements and adds the effects of all elements to construct the whole array field. The effect of changing the array element number and the beam profile are studied. Simulations considering the number of active elements have been carried out. By increasing the number of elements, main and side lobes and the distance of the maximum pressure point were increased, and the side lobes angles with the main lobe are reduced.

ACKNOWLEDGMENTS

The authors acknowledge the support of the CNMP by Research Grant PN II ADBIOSONAR, No.12079/2008.

REFERENCES

Bauer S., Gerhard-Multhaupt R., Sessler G. M., Ferroelectrets: Soft Electroactive Foams for Transducers, *Physics Today*, 57 (*2*) pp. 37-43, 2004.

Behnam H., Tajvidi E. M., Simulation of acoustic fields from 2D-array transducers with continuous wave excitation in homogeneous medium, *Electronic Journal «Technical Acoustics»*, 14, http://www.ejta.org, 2007.

Drinkwater B.W., Wilcox P.D., Ultrasonic arrays for non-destructive evaluation: A review, *NDT&E International*, 39, pp 525–541, 2006.

Helversen D.V., Holderied M.W., Helversen O.V., Echoes of bat-pollinated bell-shaped flowers: conspicuous for nectar-feeding bats?, *The Journal of Experimental Biology*, 209 (6), pp. 1025-1034, 2006.

Jensen J. A., Field: A program for Simulating Ultrasound System", *10th Nordic-Baltic Conference on Biomedical Imaging, Medical & Biological Engineering & Computing*, 1996, pp. 351-353.

Jensen, J.A., Users' guide for the Field II program, Technical University of Denmark, DK-2800 Lyngby, Denmark, http://www.es.oersted.dtu.dk/staff/jaj/field/, 2001.

Onose L., Moraru L., Nicolae M.C., Simulation of Acoustic Fields from Medical Ultrasound Transducers, Romanian *Journal of Biophysics*, 19 (4), pp 277-283, 2009, http://www.biophysicsnet.ro/rjb/number_articles.php?id_num=32

Paajanen M., ElectroMechanical Film (EMFi) - a new multipurpose electret material, *Sensors and Actuators*, 84, pp. 95 - 102, 2000.

Rao M., Varghese T., Zagzebski J. A., Simulation of ultrasound two-dimensional array transducers using a frequency domain model, *Med. Phys.*, 35 (7), pp. 3162-3169, 2008.

Ratsimandresy L., Mauchamp P., Dinet D., Felix N., and Dufait R., A 3MHz two dimensional array based on piezocomposite for medical imaging, in *Proc. IEEE Ultrason. Symp.*, pp. 1265–1268, 2002.

Ratsimandresy L., Felix N., Dinet D., Dufait R., 2D arrays performances optimization to address high quality volumetric imaging, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 521(2), pp 2199-2210, 2005

Reinhard L., Streicher A., Sutor A., Broadband ultrasonic transducers, *Proceedings of 19th International Congress on Acoustics*, Madrid, 2007.