SIMULATION OF FRESNEL BASED BEAM FOCUSING AND STEERING FOR A CROSSED ELECTRODE ARRAY

K. Latham [*1], R. Zemp [†2], J. Brown [‡1]
[1]School of Biomedical Engineering, Dalhousie University, Halifax, Canada
[2]Electrical and Computer Engineering, University of Alberta, Edmonton, Canada

1 Introduction

Fresnel based beamforming has been investigated for use as a steerable lens for 3D imaging arrays. Acoustic waves, like light, can be focused using a Fresnel lens or zone plate approach. Fresnel zone plates are capable of producing a tight focus, especially when using large aperture. A zone plate is made up of rings or strips of alternating transmissive and opaque regions. The waves diffract around the opaque zones and, because of the specific spacing, constructively interfere around the focus. In a phase zone plate both zones transmit the wave, however, there is a phase reversal for every other zone. This type of plate has the advantage of greater efficiency [1] and is a good approach for passive ultrasound focusing.

Implementing a Fresnel zone plate approach in an ultrasound transducer requires control of the pulse polarity. Arrays built on either electrostrictive ceramics or CMUTs are appropriate for this approach because the response is controlled by a DC bias. Electrostrictive ceramics such as PMN-PT (lead magnesium niobate-lead titanate) ceramic can be used as the array substrate in place of conventional piezoelectrics. This type of material is only piezoelectrically active while a bias voltage is applied and the response is tunable with the amplitude of the bias voltage. When no voltage applied the transducer, the response is negligible, and when a DC bias is applied, the phase of the acoustic wave produced is quantized to either +90 or -90 degrees, depending on whether the bias is positive or negative. Array elements defined on an electrostrictive substrate can therefore be addressed individually and in parallel. This allows for reconfigurable Fresnel zone plates to be created by varying biasing patterns.

Typical linear-phased arrays use an acoustic lens to improve the elevational slice resolution (thickness) of the image. If an elevation lens could be reconfigured to steer to moderate angles a 3D volumetric image could be captured without adding additional beamforming channels and only moderately increasing the number of electrical connections. This can be accomplished by replacing the mechanical acoustic lens with an electrically reconfigurable lens, which approximates a Fresnel lens. A Fresnel lens is created by applying the appropriate pattern of positive and negative biases along the elevation direction of the array which determine the polarity of the pulses from each element. In implementation, the array would have a set of bottom electrodes running orthogonal to the top electrodes, similar to a crossed electrode array [2]. The bottom electrodes provide the active lens control in the elevation plane and the result is an array that requires approximately 2N (or ~128) electrical connections. The alternative approach to capturing 3D image volumes is to use a 2D array with N^2 (or ~4096) elements. The low beamforming complexity and minimal electrical connectivity used in our approach provide an enormous practical advantage over conventional 2D array designs.

2 Methods

The bias value for each element is calculated by considering the geometric path length between the element and the focus. The relative phase delay for that element is given by (1).

$$\varphi = 2\pi\left[z - \sqrt{x^2 + y^2 + z^2}\right]/\lambda \qquad (1)$$

Where x, y and z are the coordinates of the desired focus relative to the array element and λ is the wavelength of the centre frequency of the excitation pulse in the medium. The sign of the bias (S_{bias}) is given by (2).

$$S_{bias} = sign[mod(\varphi + offset, -2\pi) - \pi] \qquad (2)$$

Here we are approximating the relative phase delay for each element as the portion that falls within a single wavelength (quantized as shifted by $+\pi/2$ or $-\pi/2$ radians). This models the purely transparent regions and the pulse inverted regions of the zone plate. An offset phase can be added in the calculation that shifts the reference phase of the center element [3], [4]. Consequently, there is not one unique Fresnel pattern for a given focal point. The pattern can be chosen to optimize different beam shapes (e.g. main lobe width, side lobe level, sensitivity).

Field II [5], [6] was used to simulate the Fresnel aperture as a steerable lens. The Fresnel aperture was simulated by setting the apodization values to correspond to the sign of the bias for each element as described above. These simulations were completed for a 40MHz array with λ pitch, 64 azimuthal elements and 64 elevational elements. The peak absolute pressure is plotted in the radiation patterns.

3 Results

The most promising results were obtained by switching the side of the array that receives the bias and the side of the array that carries the signals between transmit and receive events. This technique is advantageous since it produces equivalent beam profiles in both the azimuthal and elevational directions. In practice, the Fresnel aperture will focus in azimuth on transmit while the elevational elements are beamformed traditionally. Between transmit and receive events the signals switch sides. The biases are then applied in elevation and dynamic receive beamforming can be completed in azimuth. A two-way focus is achieved.

[*] kate.latham@dal.ca [‡] j.brown@dal.ca
[†] rzemp@ualberta.ca

Representative radiation patterns and beam profiles simulating this technique are shown in Figure 1. The results were compared with a 4096 element (64x64) fully sampled and beamformed array. The -6dB beamwidths using the Fresnel aperture were 102, 116 and 140 µm when steered to 0, 15 and 25 degrees respectively. For comparison, the 4096 element array had simulated beamwidths of 89, 92 and 96 µm for the same set of steering angles. The side lobe levels raised by approximately 15dB using the Fresnel approach. Sensitivity remained mostly unaffected as the received energy amplitude is comparable.

4 Discussion

The Fresnel aperture simulations show that a two-way focus can be achieved in each imaging plane with beamwidths comparable to a conventionally beamformed 2D array. This steerable lens technique could generate 3D images with only 64 signal channels and 64 bias channels. The array performance in the simulated angle range is comparable to that of a conventional 2D array that requires 4096 channels.

Switching the bias dimension with the signal dimension between transmit and receive minimizes the negative effect of the approximations made with the Fresnel aperture. Using this approach the beamwidths in azimuth and elevation are equivalent. Additional improvements can be made by carefully choosing the Fresnel pattern. As mentioned previously, a Fresnel pattern for a given focal location is not unique. The beam characteristics can be improved for a given focal point by choosing the optimal Fresnel pattern.

The theory for the Fresnel zone plate is based on continuous wave operation. There are challenges when applying the technique to pulsed ultrasound imaging. The most obvious is a degradation in pulse bandwidth at the expense of lateral resolution at the focus. This is especially detrimental when steering to wide angles where the path length differences are larger. A novel technique has been developed that preserves the pulse bandwidth at larger steering angles, correcting for the beamforming errors inherent in the Fresnel approach.

5 Conclusion

Fresnel based focusing and steering is an interesting approach to ultrasound imaging in three dimensions. The simulations in this study show the potential performance of a steerable lens technique that limits the complications in both array fabrication and beamforming electronics. The planned future work for this project includes validating these simulations with experimental results using an electrostrictive array.

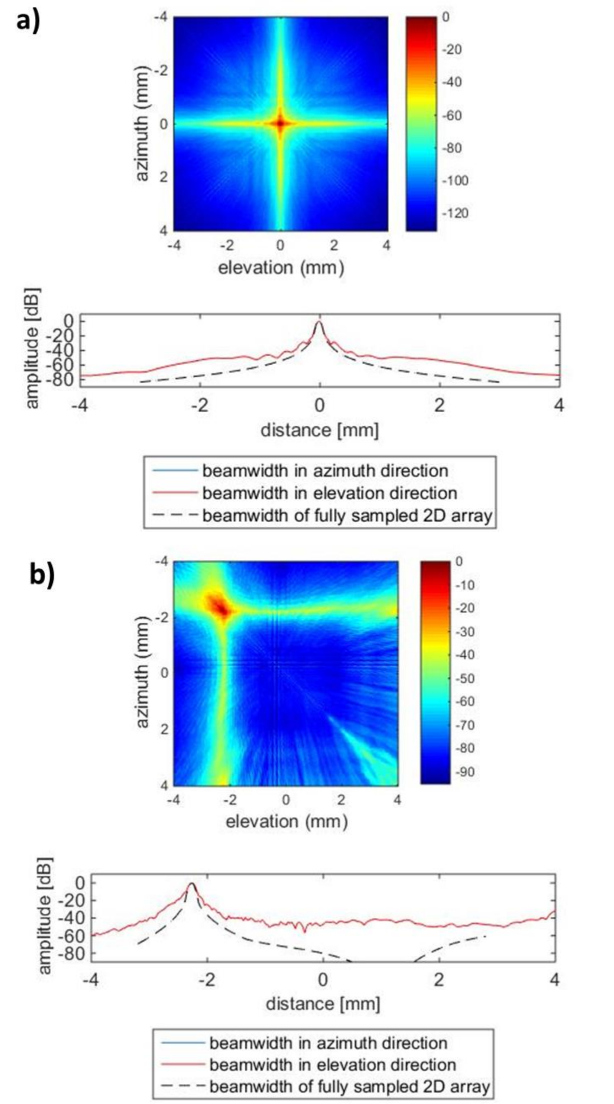

Figure 1: Two-way radiation pattern in the elevation-azimuth plane and beam profile for the array using a steerable Fresnel aperture focused a) on axis and b) to 20 degrees in both planes.

References

[1] H. D. Hristov, *Fresnel Zones in Wireless Links, Zone Plate Lenses and Antennas*. Boston: Artech House, 2000.

[2] C. E. Morton and G. R. Lockwood, "Theoretical assessment of a crossed electrode 2-D array for 3-D imaging," in *Ultrasonics, 2003 IEEE Symposium on*, 2003, pp. 968–971.

[3] C. Emery, R. Lahman, and J. Kook, "Therapeutic and diagnostic electrostrictor ultrasonic arrays," WO 2008/033528 A22008.

[4] C. Daft, P. Wagner, S. Panda, and I. Ladabaum, "Elevation beam profile control with bias polarity patterns applied to microfabricated ultrasound transducers," in *IEEE Symposium on Ultrasonics, 2003*, 2003, pp. 1578–1581.

[5] J. A. Jensen, "Field : A Program for Simulating Ultrasound Systems," *Pap. Present. 10th Nord. Conf. Biomed. Imaging. Pap. Publ. Med. Biol. Eng. Comput.*, vol. 34, no. Supplement 1 Part 1, pp. 351–353, 1996.

[6] J. A. Jensen and N. B. Svendsen, "Calculation of pressure fields from arbitrarily shaped, apodized, and excited ultrasound transducers," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 39, no. 2, pp. 262–267, 1992.