

Optimum Protocols in the Design of 2-D Spherical-Sectioned Phased-Array for 3-D Focused Ultrasound Surgery

Mingzhu Lu, Mingxi Wan, Xiaodong Wang

The Key Laboratory of Biomedical Information Engineering of Ministry of Education

Xi'an Jiaotong University

Xi'an, 710049, P.R.China

mxwan@mail.xjtu.edu.cn mzlu@mail.xjtu.edu.cn

Abstract—Phased array offers several advantages over single focused transducer such as simultaneous multi foci, flexible focus patterns and aberration correction. This study will take the optimal schemes to elongate the focal region without grating lobes, to reduce the numbers of the channel drivers, as well as to maintain the flexible multi focus patterns. This paper presents two styles of new array structures, the 128 4-combined elements and the 128 9-combined elements, to evidently elongate the focal region without grating lobes. The combined element is formed by several nearby elements being combined as an element excited by one channel driver. In the array, each center of the combined element is shifted a basic element between two neighbor rows. The simulations of the 128 4-combined elements and the 128 9-combined elements show a same elongated focal region of $18 \times 18 \times 40 \text{ mm}^3$, 10 times of that of an ordinary no-center-shift array. In addition, the 128 4-combined elements and the 128 9-combined elements can steer the C-shape multi foci very well. In further optimization, this study presents the 256 4-combined elements which can well steer up to 16 foci of fit-to-shape square multi foci, and steer the single focus laterally in a range of 34 mm and axially in a range of 46 mm without grating lobes.

Keywords-Phased Array; Focused Ultrasound Surgery; Optimal Design; Spherical Section

I. INTRODUCTION

Currently, focused ultrasound surgery (FUS) has become a promising surgical modality to ablate deep-seated tumors noninvasively [1]. Specifically, the phased array offers several advantages over single focused transducer, such as electronically steering the foci in three dimensional spaces, providing the sub-array modalities to avoid the beam obstacles like human rib cages, as well as correcting the beam distortions caused by focused beam through the human skull and tissue inhomogeneity [2-4]. To correct the distortions arising from the transmission through skull bone, the large apertures with hundreds of phased arrays were employed.

In order to have the freedom to control the ultrasound in three dimensions, the array element size needs to be small. Theoretically, the element center-to-center spacing should be equal to or smaller than half wavelength, as a result the high intensity gain therapeutic array has a large number of total elements, sometime more than 10,000 elements, and hence a

large number of total channel drivers are needed. To reduce the number of the driving wires, a special technique was developed in paper [5]. The technique included only four phase signals through quantizing the phase and phase assignment protocol, as a result only 33 input wires were used to drive the 10,000 element phased array [5]. Usually, the size of therapeutic transducer is larger than one wavelength and the phased array may have more than two hundred elements. In that case, several approaches were developed previously to suppress unwanted grating lobes. Those approaches included the sparse random placement of array elements [6], the hexagonal and quasi-random element distributions [6].

For the practical application purpose, this study will take the optimal schemes to elongate the focal region without grating lobes, to reduce the numbers of channel drivers, as well as to maintain the flexible multi focus patterns. In the following section, a new array structure and the element distributions of special design will be presented to achieve above aims. Then, the simulation results will validate the improved acoustic performance. Other protocols for the optimum element size, frequency, radius of curvature and element distribution are obtained resulting in the applicably elongated focal region and the complex multiple foci patterns.

II. STRUCTURE AND ELEMENT DISTRIBUTIONS

For spherical-section phased array, the focus can be steered around a geometrical focus region, where the focus intensity level is higher than the intensity level needed for ultrasound surgery. We usually call this geometrical focus region the focal region. Therefore, to assure the beam steering in the focal region without grating lobes, the element size of the spherical-sectioned array can be larger than a half wavelength. The smaller the element size is, the larger the focal region will be; hence the element number will increase greatly. The main optimal protocol in this study is only to arrange the centers of the elements in a certain style, while maintaining other parameter unchanging for the aim of an elongated focal region.

Fig. 1 shows the usually used ordinary spherical-sectioned phased array. Each center of element in Fig. 1 has no shift between the two neighbor rows.

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One element in Fig. 1 is divided into 4 elements in Fig. 2. The basic elements in Fig. 2 are 612 elements. Our new design protocol is to form a 128 4-combined element array. The 4-combined element is formed by the 4 nearby elements being combined as an element excited by one channel driver; and the basic elements in a 4-combined element are in electrically parallel connection. The center of each 4-combined element shown in Fig. 2 is presented by a dot (small circle). The distribution of the element centers are in a style that each center of a 4-combined element is shifted a basic element between the two neighbor rows.

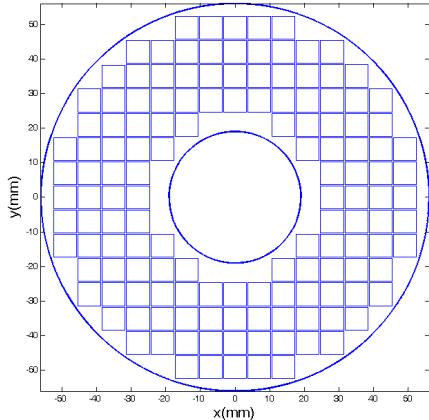


Fig. 1. The ordinary phased-array elements are distributed evenly in the projection plane without the element center shift between the two neighbor rows. The array has 112 mm aperture outer diameter, 38 mm diameter of central hole and the element square size of width 6.9 mm.

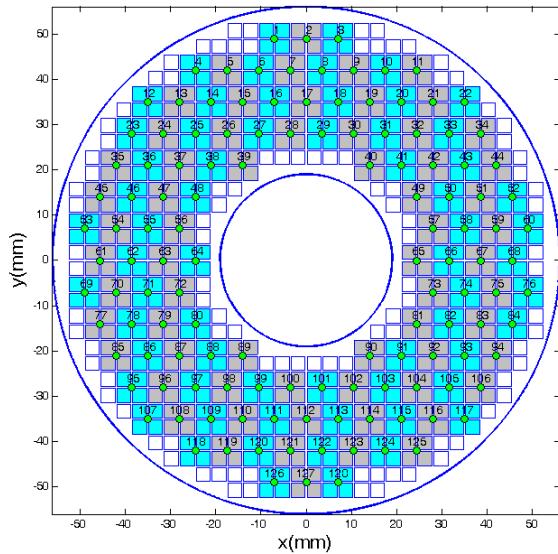


Fig. 2. A combined element is formed by 4 nearby elements. The 128 4-combined elements are distributed in a manner that each center of a 4-combined element is shifted a basic element between the two neighbor rows. The array has 612 basic elements with the element square size of width 3.4 mm.

One element in Fig. 1 is divided into 9 elements in Fig. 3. The basic elements in Fig. 3 are 1516 elements. The 9-

combined element is formed by the 9 nearby elements being combined as an element excited by one channel driver; and the basic elements in a 9-combined element are in electrically parallel connection. The distribution of the element centers are in a style that each center of a 9-combined element is shifted a basic element between the two neighbor rows. For comparison purpose, all the arrays in Fig. 1, 2 and 3 have the same 112 mm aperture outer diameter, 38 mm diameter of central hole, 125mm radius of curvature and 1.3MHz of frequency.

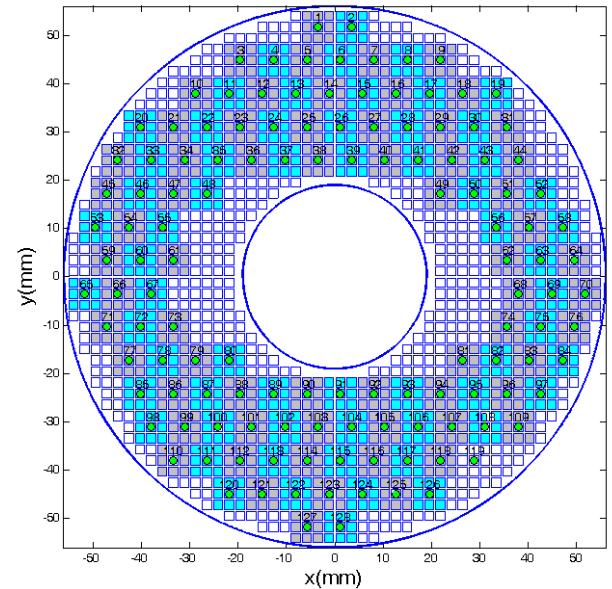


Fig. 3. The 128 9-combined elements are distributed in a manner that each center of a 9-combined element is shifted a basic element between the two neighbor rows. The array has 1516 basic elements with the element square size of width 2.2 mm.

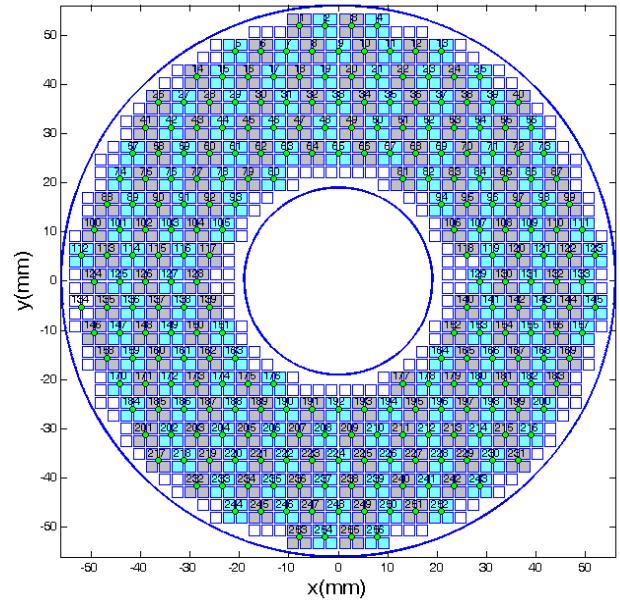


Fig. 4. The 256 4-combined element phased array with 1164 basic elements and the basic element square size of width 2.5 mm.

Further optimizing the other array parameters such as, the number of elements, radius of curvature and frequency; we have a 256 4-combined element array shown in Fig. 4. The array in Fig. 4 has the same aperture outer diameter as that of Fig. 2, the basic element square size of width 2.5 mm, 256 4-combined-element number, 100 mm of radius of curvature and 1 MHz of frequency.

III. FIELD CALCULATION AND OPTIMAL MULTIFOCUS CONTROL

For the field calculation of a spherical-sectioned phased array, an efficient field-calculation formula of the explicit expression which comes from Rayleigh-Sommerfeld integral was previously developed, which is formed as [7]:

$$p = \frac{j\rho ck}{2\pi} \sum_{n=1}^N u_n \frac{F_n \Delta A}{R_n} e^{-(\alpha+jk)R_n} \sin c \frac{kx_{sn} \Delta w}{2R} \sin c \frac{ky_{sn} \Delta h}{2R}. \quad (1)$$

where p is the complex acoustic pressure at a point, $j = \sqrt{-1}$, ρ and c are the density and sound speed in medium respectively, $k = \omega/c$ is the wavenumber, N is the number of element, α is the sound attenuation coefficient, u_n is the particle velocity of nth array element. Ref. [7] gives more details of the other parameters' calculation.

Previously, we developed a genetic optimal algorithm [8] which can be used in controlling multi foci. The combined method of combining formula (1) with the genetic optimal algorithm [8] is used to steer the multi flexible foci in the spherical -sectioned phased arrays in this study. We can first design the position of focus plane and design the multi focus positions in the focus plane, and set the wanted acoustic power, then we use the combined method to obtain the phase and amplitude signals of excitation signals for the maximum energy deposited in designed multi foci. Finally, we use the weighting algorithm based on paper [9] to get improvement in the array excitation efficiency.

IV. RESULTS

In the simulations, the 200 watts of total acoustic power and 0.02Np/cm/MHz of attenuation coefficient were applied.

In the case of the ordinary array in Fig 1, the single focus can be steered laterally in a range of 8.4 mm and axially in a range of 18 mm without grating lobes. Therefore the focal region of Fig. 1's array is $8.4 \times 8.4 \times 18 \text{ mm}^3$.

Fig. 5 shows the intensity profile of Fig. 2s' single off axial focus at (8, 0, 125)mm. The acoustic performances of Fig. 5 are a single focus without grating lobes, the focus intensity of 634 W/cm^2 , and the half maximum pressure focus dimension of $1.75 \times 1.75 \times 18 \text{ mm}^3$. For this 128 4-combined element case of Fig. 2, the single focus can be steered laterally in a range of 18 mm and axially in a range of 40 mm without grating lobes.

Fig. 6 shows the intensity profile of Fig. 3s' single off axial focus at (8, 0, 125)mm. The acoustic performances of Fig. 6 are a single focus without grating lobes, the focus intensity of 740 W/cm^2 , and the half maximum pressure focus dimension of $1.75 \times 1.75 \times 18 \text{ mm}^3$. For the 128 9-combined element case of Fig. 3, the single focus can be steered laterally in a range of 18 mm and axially in a range of 40 mm without grating lobes.

The simulation results show the 128 4-combined elements and the 128 9-combined elements have the same effectively

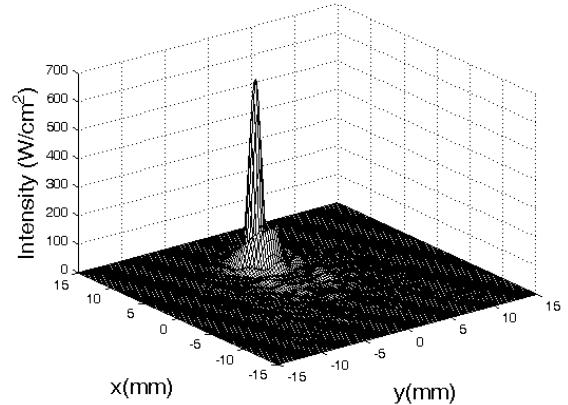


Fig. 5. Intensity profile of the 128 4-combined-element array with single off-axial focus at (8, 0, 125)mm.

elongated focal region of $18 \times 18 \times 40 \text{ mm}^3$, 10 times of that

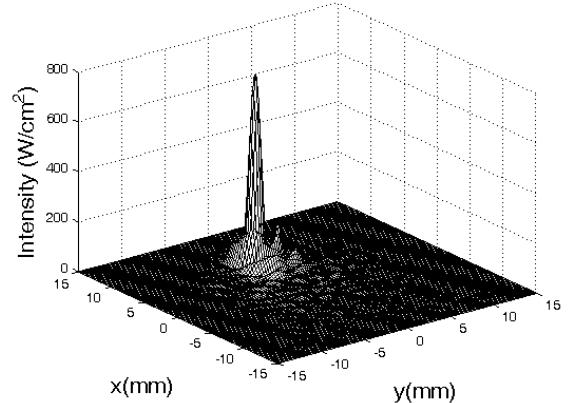


Fig. 6. Intensity profile of the 128 9-combined-element array with single off-axial focus at (8, 0, 125)mm.

of the ordinary array.

For further optimizing case, Fig. 7 shows the intensity profile of Fig. 4s' single off axial focus at (10,10,100)mm. The acoustic performances of Fig. 7 are a single focus without grating lobes, the focus intensity of 590 W/cm^2 , and the half maximum pressure focus dimension of $1.75 \times 1.75 \times 11 \text{ mm}^3$. For the 256 4-combined element case of Fig. 4, the single focus can be steered laterally in a range of 34 mm and axially in a range of 46 mm without grating lobes. The 256 4-

combined elements have elongated focal region of $34 \times 34 \times 46$ mm³, 40 times of that of the ordinary array.

The 128 4-combined elements and the 128 9-combined elements also can steer the fit-to-shape multi foci shown in Fig. 8(a). For large C-shape fit-to-shape multi foci and complex multi foci with more than 10 foci, the Fig. 8 (b) to (d) show quite satisfactory results of the 256 4-combined

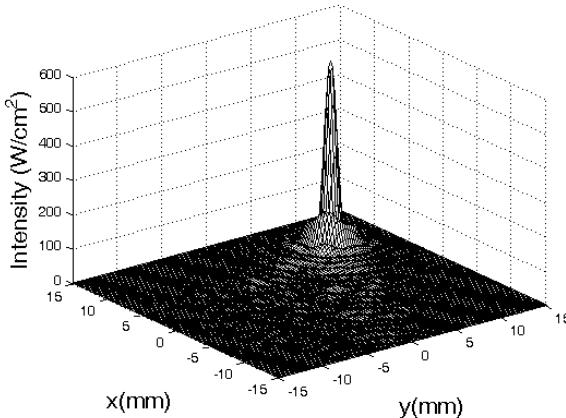


Fig. 7. Intensity profile of the 256 4-combined-element array with single off-axial focus at (10, 10, 100)mm.

elements.

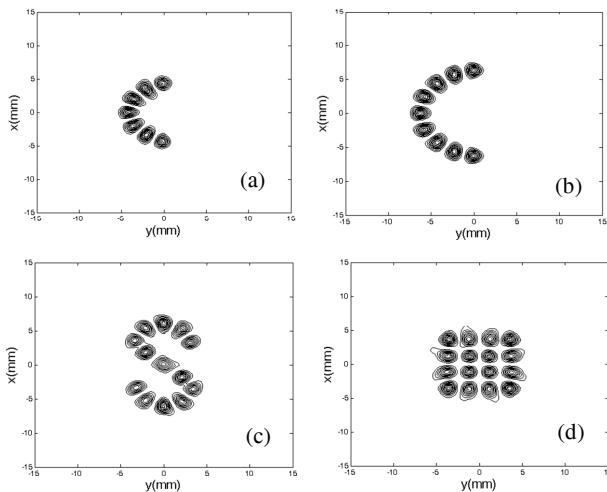


Fig. 8. The x-y intensity contour plots of the fit-to-shape multifocus patterns:(a) C-shaped 7-focus pattern with the 128 4-combined elements; using the 256 4-combined element in plots of: (b) C-shaped 9-focus pattern, (c) S-shaped 13-focus pattern, and (d) square-shaped 16-focus pattern.

V. DISCUSSION AND CONCLUSION

The simulation results validate that the combined element distribution of each combined element center shift a basic element between the two neighbor rows will evidently

elongate the focal region. This combined-element structure is our main effective optimal scheme.

The 4-combined or 9-combined array structures can be selected in 2D phased array design. Because the 128 4-combined elements and the 128 9-combined elements have the same elongated focal region, we prefer to choose the 128 4-combined elements for the easy implementation.

Although the 128 4-combined elements and the 128 9-combined elements steer the fit-to-shape multi foci very well, when the number of foci is increasing to more than 10 and multi foci are asymmetrically distributed, the number of 128-element drivers is not great enough to subside the level of side lobes. Therefore we have a 256-element array. The 256 4-combined elements in Fig. 4 can well steer up to 16 foci of the fit-to-shape square multi foci, and steer a single focus laterally in a range of 34 mm and axially in a range of 46 mm without grating lobes. Those acoustic performances of the 256 4-combined elements are qualified for the application ultrasound surgery purpose.

The number of combined elements in the array can be less than 128, however in this case, the array can not steer flexible multi foci well.

When the weighting algorithm in simulations is used, the single focus excitation efficiency can be improved to 100%, and multifocus excitation efficiency reaching 70%.

In the future work, the further elongation the focal region is still possible and can be implemented by the method of the sparse array.

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