

MODELING OF 2D ARRAY TRANSDUCER FOR BEAM OPTIMIZATION IN 3D ULTRASOUND IMAGING

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ABSTRACT

Ultrasound imaging has become an effective imaging system in medicine. The ultrasound images are generally created in two-dimensional format; however three dimensional images offer better observation and interpretation. To create three-dimensional images, special transducers with two dimensional arrays should be used. These transducers consist of piezoelectric elements arranged in two dimensions. Since the construction of such two dimensional transducers are complex, simulation of these transducers is an appropriate way to analyse and optimize their beam pattern for a particular application.

In this study, we first derived all the equations related to the construction of beam pattern of the transducers and then simulated them using Matlab. User-friendly software has been developed to enable user to alter the key parameters of the beam pattern such as beam width, side lobes, grating lobes and to find the optimized beam pattern for a particular application. The optimization is based on element sizes, element spacing, apodization and excitation pulses.

The result of the beam pattern optimization can be shown graphically and analyzed efficiently. This study can be used as an appropriate tool for the design of one dimensional and two dimensional array transducers.

KEY WORDS

Modelling, Ultrasound, Transducer, 2D Array, 3D Imaging.

1. Introduction

One major problem associated with 2D real-time imaging is that the small field of view inhibits the presentation of neighboring anatomy. Clinical interpretation of examination results as multiple two-dimensional images is difficult. To solve his problem, three-dimensional imaging has been developed that shows tomographic spatial relationships and expands the field of view.

In one approach the three-dimensional images or multiplanar views are reconstructed from a series of 2D

scans through a process similar or the 3D work that has been done in x-ray CT during the past several years. A linear array transducer is mounted on a mechanical apparatus that translates it in one direction across the imaging volume.

Multiple scan planes perpendicular to the plane of motion are collected. Several seconds are required to accumulate the scan data. The real-time imaging is forfeited and moving interfaces become problematical. Uneven body surfaces also present difficulties.

A second approach to acquire topographic information is to construct a scanning system that sweep the ultrasound beam through the tissue volume by rotating the scanhead. Transducers of this type are called volumetric transducers. A third approach is to use a rectangular-array transducer. Ultrasound beam sampling direction is electronically controlled with the appropriate crystal-firing sequence. Matrix arrays offer the potential for data collection in orthogonal planes [1], [2], [3].

In this method piezoelectric ceramics are located in two directions. Since these elements transmit ultrasound beam in two dimensions, data are received in three dimensional form and they can provide images with more capabilities than one dimensional array. As the active elements are swept throughout the field of imaging, they can construct the perfect image of the object.

The three dimensional image data can be received and processed without moving the transducer; and co processing is necessary to achieve clinically applicable frame rates. Therefore, it doesn't need localizer to detect the location of the transducer.

Each piezoelectric element produces an ultrasound field. By studying the form of this ultrasound beam, it is possible to change image parameters [2], [3].

In two dimensional array, final form of beam pattern will be the result of interference of radiated beam from each element. Some factors such as: the shape of element, elements spacing, the size and number of the elements, excitation amplitude, and etc can change the beam pattern [4], [5], [6].

The design requirement for ultrasound array transducers is to use the beam pattern simulation. It is possible to optimize its pattern for a particular application. For this purpose a software has been developed which demonstrates the ultrasonic intensity variations of radiated

beam from the designed array transducer in form of two-dimensional and three-dimensional displays [7], [8].

2. Sound Field Calculation

The method developed as a part of this study provides the field for an acoustic source which can be divided into rectangular elements [4], [5], [6]. The sound pressure amplitude, P_o at a point is given by:

$$P_o = \frac{j\rho c}{\lambda} \int_s u \frac{e^{-(\alpha+jk)r}}{r} ds \quad (1)$$

Where the integration is over the complete radiating surface s , ρ is the density of medium, c is the phase velocity of the sound waves, u is the velocity amplitude of the piston, λ is the wavelength, k is the wave number, α is the attenuation coefficient, and r is the distance between the field point and an element area.

In this study the source was divided into a number of rectangular elements in two dimensions.

The total pressure P_o at a point in the field is the sum of the pressure contributed from each element.

$$P_o = \frac{j\rho c}{\lambda} \sum_{n=1}^N \sum_{m=1}^M u(n,m) \int_{\Delta A} \frac{e^{-(\alpha+jk)r}}{r} dA \quad (2)$$

Where N and M are the number of elements of size $\Delta A = \Delta h \times \Delta w$ in X and Y axis and $U_{(n,m)}$ is the complex excitation.

The center of element is denoted by $(x_{(n,m)}, y_{(n,m)})$.

To simplify the analysis, additionally, a second coordinate system is defined in x_o, y_o with its origin centered on the element as shown in Figure 1. Using these relations in (2) yields:

$$P_o = \frac{j\rho c}{\lambda} \sum_{n=1}^N \sum_{m=1}^M \int_{-\frac{\Delta h}{2}}^{\frac{\Delta h}{2}} \int_{-\frac{\Delta w}{2}}^{\frac{\Delta w}{2}} \frac{e^{-(\alpha+jk)r}}{r} dx_o dy_o.$$

$$y - y_{(n,m)} = y'_{(n,m)}$$

$$x - x_{(n,m)} = x'_{(n,m)}$$

$$R = \sqrt{z^2 + (x - x_{(n,m)})^2 + (y - y_{(n,m)})^2}$$

$$r = \sqrt{z^2 + (x - x_{(n,m)} - x_o)^2 + (y - y_{(n,m)} - y_o)^2} \quad (3)$$

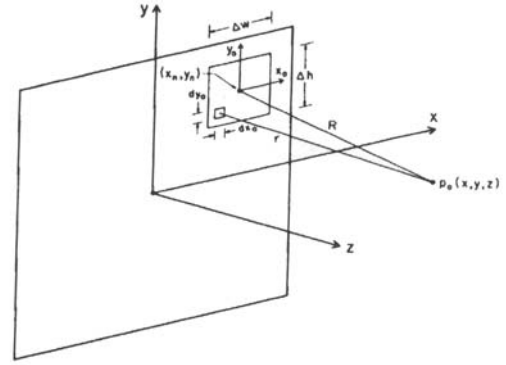


Figure 1. Coordinate system used for rectangular source.

Assumptions, which will be followed, are used to reduce integrals in (3) to Fourier transform expressions which upon evaluation yield:

$$P_o = \frac{j\rho c \Delta A}{\lambda} \sum_{n=1}^N \sum_{m=1}^M \frac{u(n,m)}{R} e^{-(\alpha+jk)R} * \sin c \frac{kx'_{(n,m)} \Delta w}{2R} \sin c \frac{ky'_{(n,m)} \Delta h}{2R} \quad (4)$$

This relation is straightforward summation of complex terms, representing the pressure due to rectangular sources shown in Figure 2. However, it is only useful if the approximations used are applicable. The three assumptions used to derive (4) are:

$$\cos\left(\frac{k\Delta w^2}{8R} + \frac{k\Delta h^2}{8R}\right) \cong 1$$

$$e^{\frac{\alpha(x'_{(n,m)}\Delta w + y'_{(n,m)}\Delta h)}{2R}} \approx 1 \quad (5)$$

$$\frac{r}{R} \cong 1$$

These conditions impose limitations on the sizes of Δw and Δh which can be used for computation.

$$\Delta w, \Delta h \leq \sqrt{\frac{4\lambda z}{F}} \quad (6)$$

The constant F represents the distance from the source to the field point relative to the distance to the near field-far field transition for a source of size of Δw .

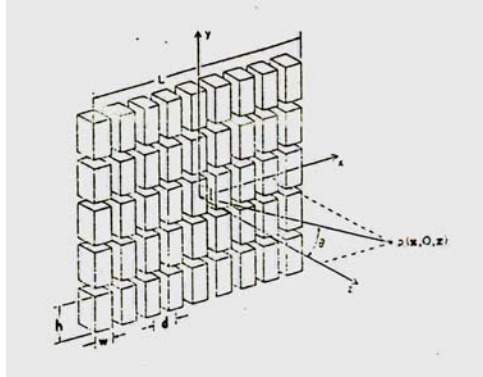


Figure 2. Two-dimensional array transducer

2.1 Focusing

Electronic focusing involves the superimposition (algebraic summation) of ultrasound waves. Each element produces a particular wave pattern. Overall pattern derived from a group of crystal is the summation of all wave patterns from individual crystals (Huygens principle). Electronic focusing is accomplished by offsetting the firing of various crystals in a group by a small delay [3].

A rectangular phase arrays are electronically focused in two dimensions along both directions of the crystal matrix. Electronic focusing is applied simultaneously, but steering is controlled in only one direction at a time. However without moving the transducer, the direction of the beam is changed electronically by altering the excitation sequence to the crystal elements. Steering the beam throughout the field of view allows for data collection from the determined focal points.

As it mentioned before $u_{(n,m)}$ is the complex excitation of all pointed sources on $(N \times M)$ elements given by:

$$u_{(n,m)} = A_{(n,m)} e^{j(\omega t + \theta_{(n,m)})} \quad (7)$$

Where $A(n,m)$ is the excitation amplitude of each element. ω is angle frequency ($\omega = 2\pi f$) and $\theta(n,m)$ is the phase of each element, which determines the delays of element excitations.

To steer the beam towards a desired focal point, $\theta(n,m)$ of each element is calculated by r and r_1 as shown in Figure 3.

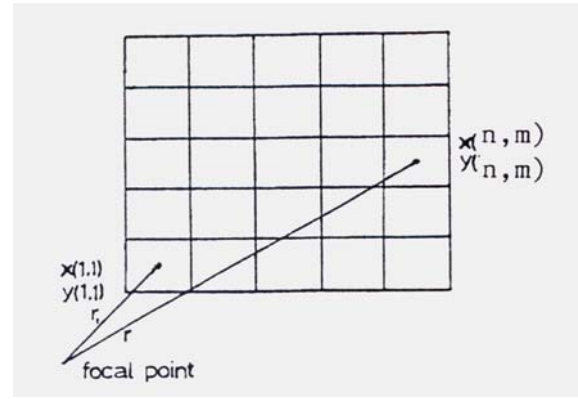


Figure 3. Time delays in linear phased arrays allow each point to become the focal point.

The first element is taken as a reference in excitation and r_1 is the distance between the focal point and the center of the first element, and r is the distance between the focal point and the center of each element. Therefore $\theta(n,m)$ for each element is given by:

$$\theta_{(n,m)} = 2\pi f \frac{|r - r_1|}{c} \quad (8)$$

Finally it leads us to:

$$u_{(n,m)} = A_{(n,m)} e^{j\left(\frac{\pi}{4} + 2\pi f \frac{|r - r_1|}{c}\right)} \quad (9)$$

The user will be able to calculate $u_{(n,m)}$ by entering the coordinates of desired focal point .

2.2 Apodization

A major problem with electronic arrays is the formation of secondary lobes of ultrasound energy. Secondary lobes originate at the transducer and radiate outward at various angles to main beam. They are typically of low intensity compared with the main beam (60 to 100 dB).

A technique called "Apodization" lowers their intensity for electronic arrays. Apodization employs a variable strength voltage pulse to the crystal across the aperture during delay line focusing, such that the highest voltage is applied to the center element and excitation voltage is reduced toward periphery (Figure4).

We normalized the highest excitation amplitude to one, which is applied to the central element of 2-dimensional array, and the amplitude will be reduced relatively toward edges with a gradient of G . For this purpose the equation (10) has been implemented where G can be defined by user. Therefore, $A(n,m)$ is given by:

$$A(n,m) = 1 - G \sqrt{\left(x(n,m) - x\left(\frac{N}{2}, \frac{M}{2}\right)\right)^2 + \left(y(n,m) - y\left(\frac{N}{2}, \frac{M}{2}\right)\right)^2} \quad (10)$$

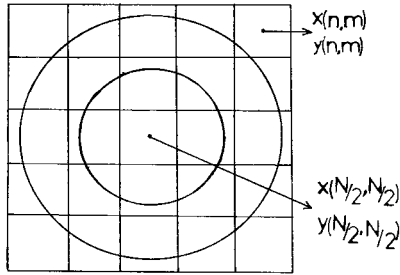


Figure 4. Apodization demonstrated by varying the strength of the voltage pulse.

2.3 Results

By implementation of the mentioned equations the acoustic pressure amplitude and the phases of each element in two dimensional array transducers are determined. Thus, the ultrasound beam radiated from the transducer can be simulated. A graphic user interface program provides a tool for the user to change effective parameters to obtain desirable beam pattern.

The following variables are the suitable parameters for optimization the beam pattern for the design of an ultrasound transducer for a required application:

- *Number of elements along X axis*

This parameter points to the number of piezoelectric elements along X axis which is denoted by N in the main equation.

- *Number of elements along Y axis*

This parameter points to the number of piezoelectric elements along Y axis which is denoted by M in the main equation.

- *Elements spacing along X axis*

This parameter points to the distance (space) between elements along X axis which is denoted by $x'_{(n,m)}$ in the equation.

- *Elements spacing along Y axis*

This parameter points to the distance (space) between elements along Y axis which is denoted by $y'_{(n,m)}$ in the equation.

- *Transducer Frequency*

This parameter points to the frequency of radiated ultrasound waves from Piezoelectric.

- *Piezoelectric Length, Width*

They are the length and the width of Piezoelectric elements showed by $\Delta\omega$ and Δh .

2.4 Experimental Results

The following two figures give examples of the output from the simulator. In Figure 6 and Figure 7 the beam patterns from the two-dimensional transducer are shown. These graphs are illustrated by substituting the following data:

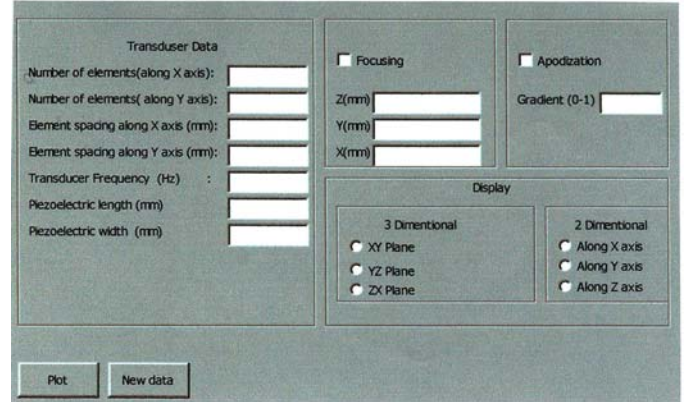


Figure 5. User menu is used to enter the parameters of simulation.

Number of elements	21×21
Size of elements	0.1 mm
Elements space	0.01 mm
Apodization Coefficient	0.9

Using this simulator is also possible to show the ultrasound intensity along any axis in the Cartesian or Spherical coordinate systems; for instance along the acoustic axis as shown in Figure 8.

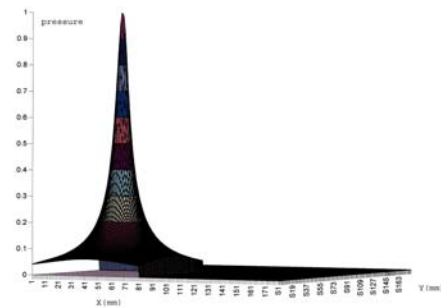


Figure 6. Beam pattern obtained by 2D array transducer at 7.5MHz

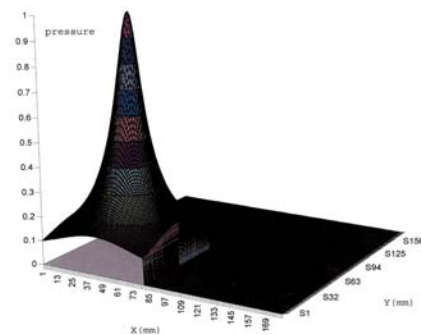


Figure 7. Beam pattern obtained by 2D array transducer at 5MHz.

The optimization can be performed by keeping some parameters constant and varying the others. The following effects are illustrated this optimization of 2D array transducers. They also show the flexibility of the simulation.

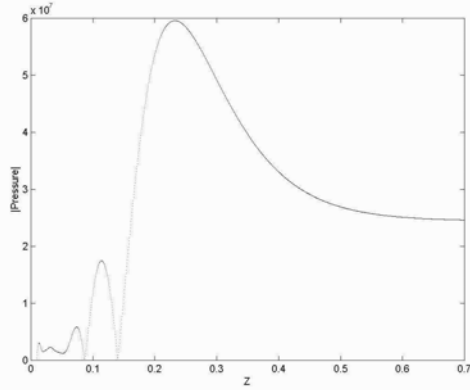


Figure 8. Intensity plot along acoustic axis

A) The effect of elements size

With the constant frequency of 5 MHz and without applying the focal point and apodization technique, the size of elements has been changed from 0.01 mm to 2 mm and we found the increase of side lobes at curves. With increasing the size of piezoelectric elements of transducer, the side lobes will be increased.

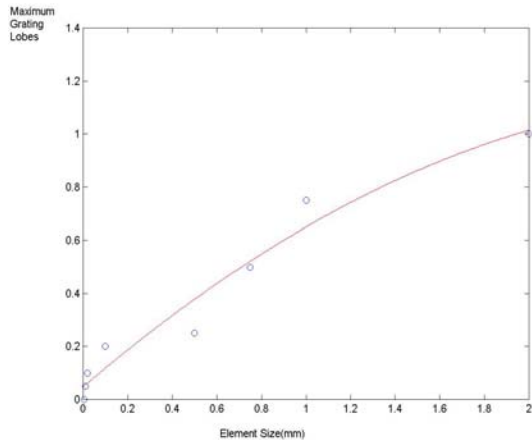


Figure 9. By decreasing of the size of elements, side lobes will reduced

B) The Frequency effect

With the constant size (0.1mm) and spacing between elements (0.01mm) and without applying any focusing and apodization ($G=1$) the frequency of elements has been changed from 1MHz to 10 MHz and beam width will be decreased and lateral resolution will be improved (Figure 10).

C) The effect of Apodization technique

With the constant frequency of 5 MHz and the size (0.1 mm) and space between the elements (0.01 mm) and without applying the focal point and exerting Apodization technique the degree of Apodization has been changed from 0 to 1. It is found that as G get closer to 1; the grating lobes will be decreased (Figure 11).

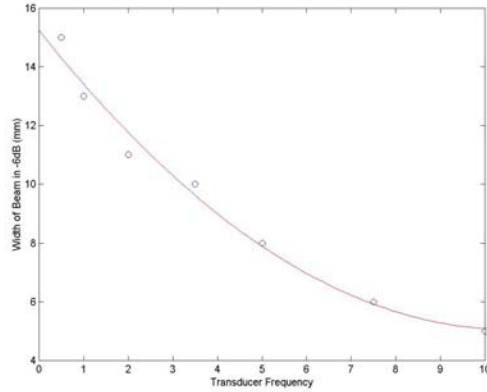


Figure 10. By increasing of the frequency, beam width will be decreased and lateral resolution will be improved.

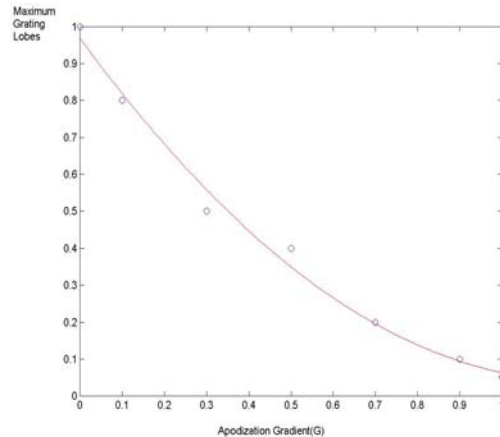


Figure 11. By increasing of apodization coefficient (G), side lobes will be reduced.

3. Conclusion

An accurate, flexible, and efficient method was applied to determine the ultrasound field of a plane source. User-friendly software has been developed to enable user to alter the key parameters of the beam pattern such as beam width, grating lobes and to determine the optimized beam pattern for a particular application. The optimization is based on element sizes, element spacing, apodization, focal point and excitation pulses.

This study can be used as an appropriate tool for the design of one dimensional and two dimensional array transducers.

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