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Ultrasound Plane-Wave Imaging Based on Linear Arrays with Variable Inter-element Spacings

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Abstract—**For ultrasound plane wave imaging, the conventional ultrasonic transducer is a uniform linear array. However, the fan-shaped artifacts which usually appear around the target point in the ultrasound image affect the observation and analysis of the image. It is one of the import issues that many researchers are trying to solve using improved plane-wave algorithms. In fact, similar issue had been studied in the field of radio antenna about linear arrays with variable inter-element spacing. In order to apply this structural design in ultrasound transducer with an expectation to improve the image quality of coherent compounding plane-wave imaging, simulation about several nonuniformities have been finished. The simulation results demonstrated that the special structural design can generate flatter wave fronts of transmitted waveforms at near field, which contributes to improving the image quality of plane wave imaging.**

Keywords—linear array, variable inter-element spacing, structural design, plane wave, ultrasound imaging

I. Introduction

Ultrasound imaging has become an increasingly major medical imaging method with imaging speed greatly improved by ultra-fast plane wave imaging technology[1]. The resolution of ultra-fast ultrasound imaging in the far field is no less than that of traditional ultrasound, but there are still some shortcomings in the imaging quality. In fact, in plane wave imaging technology, the ultrasonic transducers are mostly linear arrays with have the characteristics bellow. The size follows the traditional ultrasonic linear array design laws, and the parameters of each array element are equal, which we call a uniform linear array.

The sound field of uniform linear array has a large sidelobe level, and the waveform of the near field is not flat enough to become the theoretical plane wave shape. Thus, applying the plane wave algorithm to the near-field will lead to severe fan-shaped artifacts. This makes the hard observation of the lesion during the actual imaging process and it is difficult to solve by improving algorithm. Therefore, we re-design the structure of the ultrasound transducer to get better image of near field.

The idea of unequally spaced ultrasonic linear arrays is inspired by the concept in antenna. A variety of linear arrays have different properties in the field of antennas. Many studies of unequally spaced linear arrays have been recorded. The concept of an unequally spaced antenna is opposite to that of an uniform antenna array, which means that the pitch between antenna elements is not equal. The special array element distribution can reduce the sound field sidelobe levels or beam width values[2-4]. This new design also provides advantages such as reductions in size and number of elements. That is the reason why we choose the nonuniform structure type and we expect the design in ultrasound transducer to have similar advantages.

In the further study, we transform the unequally-spaced array into a linear array with variable inter-element spacing and modify the parameters of each array element in a deeper way.

II. Method

A. Transducer Model

In ultrasonic transducer, there is little information about the re-design of structure. Almost no mature non-uniform linear array theory exists. Therefore, the influence should be verified from the simulation level that the non-uniform settings of the array element parameters have on the acoustic field.

The simulation model selects the coupled electric field, sound field and solid mechanics part. The model uses the piezoelectric effect generated by the transducer model to get the sound field, and calculates the pressure distribution during the propagation process in a given region. The calculated sound field material is selected to be water, where the speed of ultrasonic waves is rather close to that in the human body.

Ultrasonic linear array transducers have a variety settings of non-uniformities. Here we can divide the parameters into two types, the width of the array element and the spacing between adjacent array elements, which we can also call kerf. The figure below shows the exactly meaning of these parameters. One example of linear arrays with N types of structural parameters is also demonstrated in the figure.

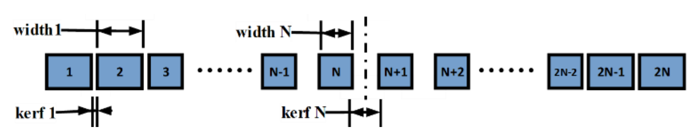

Fig.1. One example of linear arrays.

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Numerical values of variables and the distribution between array elements remain to be further studied. Here three combinations of the following parameters shown in figure2 have been chosen to verify the tendency of the sound field.

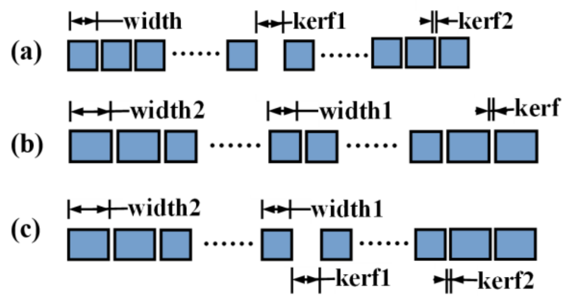

Fig.2. Three types of variable interelement spacings.

We choose the 8-element ultrasound transducer linear array on the basis of three models above. In this way, we are able to control the basic shape of the sound field and avoid to cause errors in the process of calculating iterations because of the excessive number of array elements. We adopt the regional settings shown in figure 3. The structural parameters of the middle part are the same as the uniform linear array and the elements on both sides satisfy the non-uniform parameters that will be set.

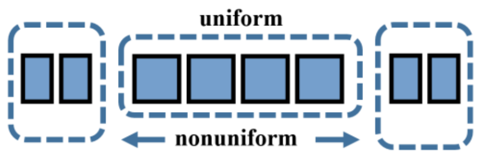

Fig.3.One configure of linear array with variable interelement spacings.

From the settings above, the structural parameters of the ultrasonic linear array transducer are summarized in the following table. Among them, kerf1 refers to the spacing of the adjacent elements in the uniform part, and kerf2 refers to the spacing of the remaining elements on both sides. Width1 and width2 refer to the structural parameters of the same area.

TABLE I. STRUCTURAL PARAMETERS OF LINEAR TABLE TYPE STYLES

Structural parameters	Uniform	Nonuniform1	Nonuniform2	Nonuniform3
kerf1(um)	25	25	25	25
no. of kerf1	8	8	4	4
Kerf2(um)	—	—	15	15
no. of kerf2	—	—	4	4
width1(um)	300	300	300	300
no. of width1	8	4	8	4
width2(um)	—	200	—	200
no. of width2	—	4	—	4

The purpose of the simulation is to obtain the sound field distribution of the near field (~10mm) from the transducer surface, which requires high accuracy of calculation. Therefore, we divide the propagation medium into meshes with smaller unit size. The largest unit size is set up to 20um and the minimum unit size is 1.65um. While the internal mesh of the piezoelectric transducer can be increased to some extent. The size is set to 60um to simplify the calculation inside the transducer. This way to allocate the size of the mesh will save computing resources and reduces the probability of error in iterative calculations.

B. Imaging Simulation Settings

From the theoretical analysis of plane wave imaging algorithm, it is acknowledged that the flatter the wave front in the near field is, the more accurate of plane wave imaging algorithm becomes. Wider field and more concentrated energy will also bring improvement. Accordingly, the significant improvement of the image quality of non-uniform array should be reflected in the near field. So the imaging is verified below and the quality would be validated with the simulation software Field II[5].

In order to observe the image at different positions, scatter points are set at different depths and different width of the phantom. The phantom is shown in the figure.4.

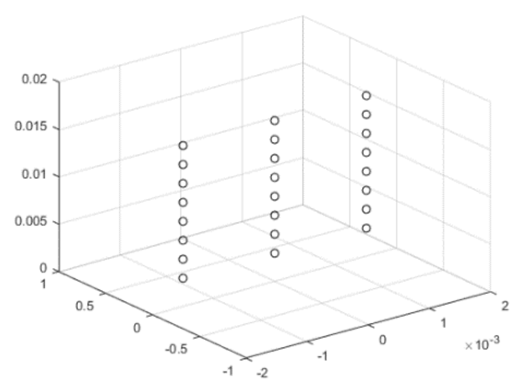

Fig.4. Distribution of scatter points in a 3-D phantom.

We apply the general laws obtained from the sound field simulation to the image simulation experiment. When setting up the transducer, it shall be as close as possible to the technology that can be achieved by the actual linear array, and the parameter settings of sound field simulation should be taken into account. Therefore, we choose a linear array of 32 elements with the center frequency of 12MHz, and the data sampling rate is set to 4 times the center frequency. According to the rule deduced previously, the pitch was modified as same as the table 1 mentioned before.

III. RESULTS

A. Results of Soundfield

The results are shown as follows. With the increasing number of changing parameters, the difference between the beam shape of near-field and ideal plane wave becomes smaller.

The results show a trend: the width and spacing of the array elements obey a general non-uniform distribution law which shall be studied further in the future. Under the law, the wavefront is more evenly distributed, especially the place near the transducer surface where can form a nearly ideal plane wave waveform.

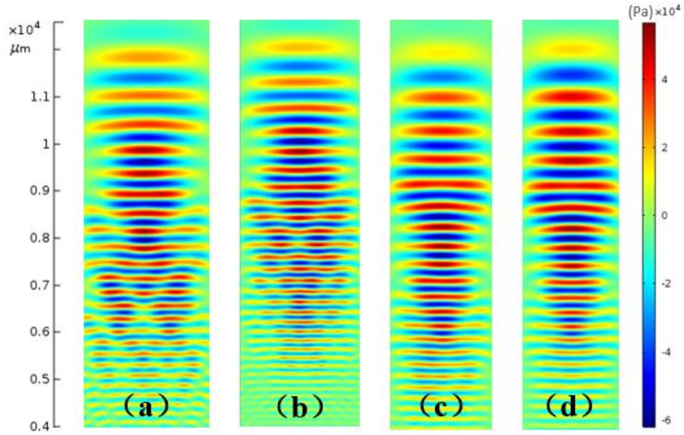

Fig.5. Sound field of transducers with different non-uniformities at the same time. (a) uniform linear array transducer, (b) linear arrays with various kerfs, (c) linear arrays with various widths, (d) linear arrays with various widths and kerfs.

B. Results of Imaging

The non-uniform linear array with the best imaging results in current simulation is compared with the uniform linear array. All the images are produced without modification of signal filters and the comparison is shown in figure.6.

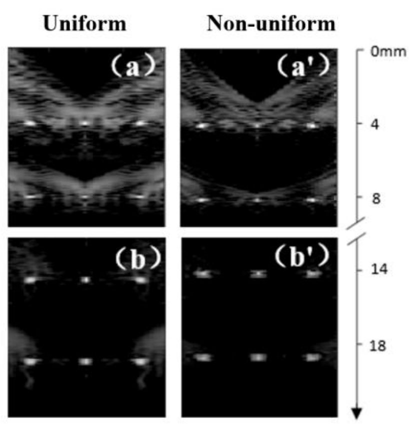

Fig.6. Comparison between uniform and non-uniform linear arrays. (a) and (b) are simulation results of uniform linear array.(a') and (b') are simulation results of non-uniform linear array.

The near field of ultrasonic imaging can be approximately defined within 0~20mm. In this region, the artifacts of the non-uniform linear array are apparently improved. Separately, at the depth of 8mm, the imaging effect in the center of the field of view is significantly better than that on both sides, where the area and brightness of the artifacts are greatly reduced. At the depth of 19mm, some changes occurred in the improved situation. Compared with uniform type, the central part of the view field shows little difference in imaging, while the artifacts on the two boundaries of B-mode images basically disappear. This means that non-uniform linear array transducers have a clearer and wider field of view compared with the conventional transducers with the same size.

IV. Conclusions

Analysis of the sound field shows that at the distance of 4mm from the transducer, the energy distribution is more uniform and regular. In this case the waveform is close to the shape of theoretical plane wave, while the energy level is as low as 1×10^4 Pa. That is why the image quality has improved, but the artifacts cannot be completely eliminated. As the wavefront propagates, the waveform gradually stabilizes and covers a wider field of view. Therefore, in the region above 10 mm, the artifacts on both sides disappear due to the widening of the sound field. The propagation also causes the energy to gradually diverge, and decreases the resolution of imaging in this area.

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