Transmit-Receive Dynamic Focusing with Limited Diffraction Beams

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Abstract — A two-way Fourier imaging method has been developed with limited diffraction beams. Resolution and sidelobes of 2D and 3D images constructed with the method are similar to those obtained with a conventional two-way dynamic focusing system if a cosine aperture apodization is applied. No delay and image montage are required for the new method and thus imaging systems will be greatly simplified.

I. INTRODUCTION

Dynamic focusing is a technique used in conventional ultrasonic imaging systems to increase image resolution and contrast [1]. This technique can only be applied to receive beamforming without reducing frame rate. If it is applied to transmission, montage of multiple frames of images is required and thus the frame rate is reduced greatly. For a conventional two-dimensional (2D) imaging system, the frame rate is about 30 frames/s without montage. If, for example, 100 frames are used for montage, the frame rate is 0.3 frames/s. For blood flow imaging, the frame rate will be further reduced because multiple A-lines are required to obtain flow information.

Limited diffraction beams are a new type of beams developed first by Stratton in 1941 [2] and can be used without montage to construct high-quality images similar to those obtained with a two-way (transmit-receive) dynamic focusing. These beams have also a large depth of field and could have applications in medical imaging [3–9], tissue characterization [10], blood flow velocity vector measurement [11,12], and other areas such as nondestructive evaluation (NDE) of materials [13], high-speed digital wireless communication [14], electromagnetism [15,16], and optics [17]. Recently, a new class of limited diffraction beams such as X waves [18–22], array beams [23–25], and bowtie beams [4–5] have been developed and their theories have been studied extensively [26–28]. Based on these new beams, a new imaging method (Fourier method) has been developed [29,30]. With the method, 2D and three-dimensional (3D) images of a high frame rate (up to 3750 frames/second for biological soft tissues at a depth of about 200 mm) can be constructed with simple, inexpensive electronics when objects are illuminated with a plane wave [29,30].

In this paper, the Fourier method is extended to both transmit and receive (two-way) beamforming to increase image resolution without montage. Sidelobes of images are reduced greatly with a cosine aperture apodization. Because the fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT) can be used to replace the conventional delay-and-sum beamforming [31] with the new method, imaging systems will be greatly simplified, especially, for 3D imaging [29,30].

II. METHOD

From the discussion in "K. Increasing Spatial Fourier-Domain Coverage" on Pages 850 and 851 and formulas (42) and (43) in Reference [29], one obtains the following steps to implement the two-way Fourier method in a practical machine (use a 1D and 2D arrays for 2D and 3D imaging, respectively):

(1) Excite each element of an array with a broadband electric discharging. The peak amplitude and the sign of the excitation signal are determined with stepwise cosine and sine functions, and the step size is determined by the inter-element distance of the array elements. For a 2D array, the sine and cosine functions may have different spatial frequencies in the two perpendicular directions of the array. The frequencies are chosen at the rectangular grids of the spatial Fourier transform of the object in the k_x' and k_y' axes (see Fig. 13 and "V. A Suggested Imaging System" on Pages 847 and 848 in Reference [29]).

(2) Weigh the received radio-frequency (RF) signal (echo) from each element with sine and cosine functions of the same spatial frequencies as in transmit. Note: to reduce sidelobes, a fixed, half-cycle cosine function (with zeroes at the edges and peak at the center of the array) can be applied to both transmit and receive aperture at the expense of a slight reduction of lateral resolution of images.

(3) Sum the received RF signals from all elements to produce a complex A-line (its real and imaginary parts correspond to the sine and cosine weightings, respectively).

(4) Digitize and then Fourier transform each A-line with the FFT.

(5) Interpolate the Fourier transform of each A-line with a nearest-neighbor interpolation algorithm [32] to obtained spatial Fourier transform of an object function

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at rectangular grids in k'_z axis (see Fig. 13 of Reference [29]).

(6) Repeat the above steps (1–5) for different spatial frequencies to cover the entire 2D or 3D Fourier space of an object function. The highest spatial frequency is limited by the inter-element distance of the transducer array elements, which in turn, determine the spatial resolution of constructed images.

(7) Construct a frame of 2D or 3D image with a 2D or 3D IFFT.

The major difference of the above method from conventional beamforming is that no delays of signals and beam steering are necessary in both transmission and reception for image constructions, and no montage is used for two-way beamforming.

III. RESULTS

To demonstrate the efficacy of the new method, a computer simulation was performed according to above procedures. In the simulation, a broadband linear array of 64–elements, 2.5 MHz, 38.4 mm wide, and 10 mm in elevation direction was used (the parameters were chosen in accordance with the array used in the experiment in Reference [30]). An object consisting of 9 point scatterers was located at the center plane in the elevation direction of the array (Fig. 1). The dimension of the object and its relative position to the array are shown in the figure. Notice that the object is larger than the aperture of the array to form a sector shaped image.

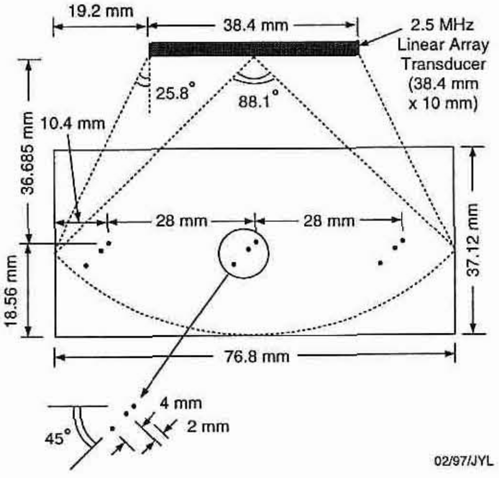

Fig. 1 Geometry of an object consisting of 9 point scatterers. A linear array is shown on the top.

Images constructed with the two-way Fourier and the conventional dynamic focusing methods are shown in the top and bottom rows of Fig. 2, respectively. Images in the left and right columns were obtained with and without a cosine aperture apodization, respectively. The apodization was a half-cycle cosine function with its peak at the center and zeroes at the edges of the array.

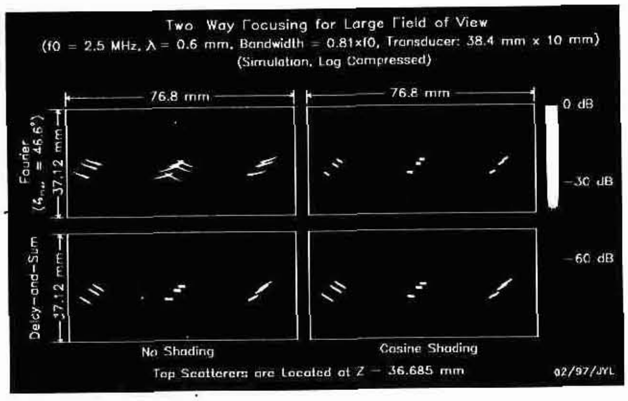

Fig. 2 Images constructed with a two-way beamforming system. Upper two panels are images obtained with the new Fourier method using limited diffraction beams. Images in the lower two panels are constructed with a conventional two-way dynamic focusing system. Panels on the left and right hand sides are images without and with a cosine aperture apodization, respectively. In the Fourier method, the maximum Axicon angle [29], ζ, is 46.6°. Analytic envelope of constructed images is displayed.

Line plots showing the lateral resolution and the maximum sidelobes of constructed images in Fig. 2 are shown in Fig. 3. The line plots are obtained by plotting the maxima of the constructed images in each vertical line over the lateral distance.

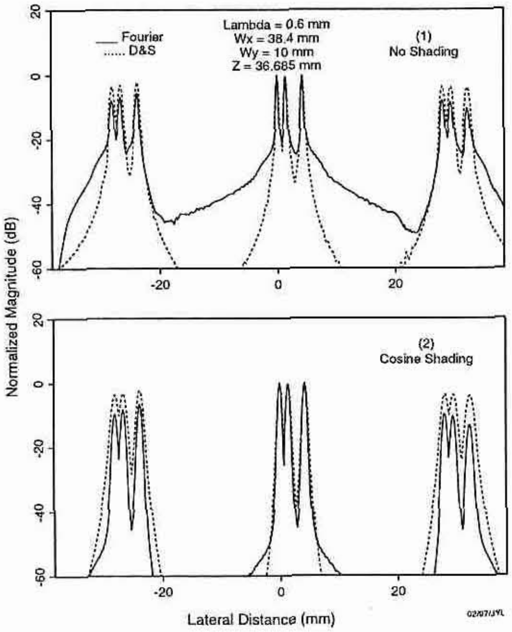

Fig. 3 Line plots of images in Fig. 2 showing resolution and maximum sidelobes in the lateral direction. Plots in upper and lower panels correspond to those images in the upper and lower panels of Fig. 2, respectively. Solid and dotted lines are results obtained with the new Fourier method and the conventional two-way dynamic focusing method.

IV. DISCUSSION

A. Resolution and Sidelobes

Results in Figs. 2 and 3 show that images constructed with the two-way Fourier method without a cosine aperture apodization have a slightly better resolution but higher sidelobes than those obtained with a conventional two-way dynamic focusing method. With a cosine apodization, sidelobes are reduced dramatically at the expenses of reduced image resolution. However, the resolution is still slightly better than that of a conventional two-way dynamic focusing method when the same apodization is applied.

B. Frame Rate

The frame rate of the new imaging method is determined by the number of A-lines required to construct a frame of image. For example, if 128 and 128×128 A-lines are used to construct a 2D and 3D images, respectively, for biological soft tissues at a depth of 200 mm, the highest frame rate is about 29 frames/s and 0.23 frames/s (assume that the speed of sound is about 1500 m/s). For conventional two-way dynamic focusing systems, the frame rate will be reduced greatly because of montage.

C. Field of View

The field of view of constructed images with the new method can be larger than the size of transducer aperture. This is different from the high frame rate imaging method [29,30] where a plane wave is used in transmission and the image field of view is limited by the plane wave illumination area.

D. Producing Limited Diffraction Beams in both Transmission and Reception

In the new method, limited diffraction beams are produced in both transmission and reception with simple sine and cosine aperture weightings at different spatial frequencies. No delays of signals in both transmit and receive are necessary. This simplifies imaging systems.

E. Aperture Apodization

From Figs. 2 and 3, it is clear that sidelobes of images constructed with the new method are reduced significantly if an aperture apodization is used. The figures also show that a cosine aperture apodization is a good compromise between resolution and sidelobes.

F. Simplified Systems

Because FFT and IFFT are used in image constructions in the new method, imaging systems will be simpler, especially, for 3D imaging.

G. Motion Artifacts

Because multiple transmissions are needed to construct a frame of image in the two-way Fourier method, images will be distorted if objects move fast. Therefore, for fast moving objects such as heart, the high frame rate Fourier method [29,30] should be used to construct both 2D and 3D (volumetric) images. The high frame rate method should also be used for blood flow imaging [29].

V. CONCLUSION

A new imaging method (two-way Fourier method) is developed. This method has a potential for high resolution and high contrast 2D and 3D imaging without montage. Because the FFT and IFFT, instead of the conventional delay-and-sum [31], are used, imaging systems will be greatly simplified. The method will also be a good compliment to the high frame rate Fourier method that is used for 2D and 3D imaging of fast moving objects and blood flow vector imaging [29,30].

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