STEERING OF LIMITED DIFFRACTION BEAMS WITH A TWO-DIMENSIONAL ARRAY TRANSDUCER

Jian-yu Lu and James F. Greenleaf

Biodynamics Research Unit, Department of Physiology and Biophysics,
Mayo Clinic and Foundation, Rochester, MN 55905

ABSTRACT

Limited diffraction beams such as Bessel beams and X waves have large depth of field and could have applications in medical ultrasound and other wave related areas. However, they are usually produced by annular arrays which have to be scanned mechanically. In this paper, the production and steering of the limited diffraction beams with a two-dimensional array are studied. Results show that good limited diffraction beams can be produced if the size of the array elements is small and the array aperture is compensated so that the projection of the aperture on a plane perpendicular to the beam axis is a constant annular ring pattern. The electronic system for controlling the two-dimensional array is described and methods to simplify it are proposed.

I. INTRODUCTION

Pencil thin beams are ideal for doing high-resolution imaging. Recently discovered limited diffraction beams such as Localized waves [1–2], Bessel beam [3–7] and X waves [8–10] have this property. They have pencil-like main lobes and descending sidelobes and can propagate to infinite distances without spreading provided that they are produced with an infinite aperture. When produced with a finite aperture, the beams continue to have large depth of field. Therefore, these beams could have applications in medical ultrasonic imaging [11–12], biologic tissue characterization [13], and nondestructive evaluation of materials [14–15].

We have produced high-resolution pulse-echo images of a tissue equivalent phantom (Model RMI413A) with a large depth of field using a J_0 Bessel beam [11]. The J_0 Bessel beam was produced by an annular array transducer with a special annuli positioning [6]. However, the annular array can only be scanned mechanically and cannot be applied to conventional phased array Doppler imaging systems.

In this paper, we report the design of two-dimensional arrays [16–18] for producing and steering limited diffraction beams. In Section II, methods of steering the limited diffraction beams with a two-dimensional array will be described. Section III reports simulation results. Section IV introduces a suggested sector scan system and Sections V and VI give a brief discussion and a conclusion, respectively.

II. STEERING LIMITED DIFFRACTION BEAMS WITH A TWO-DIMENSIONAL ARRAY

To produce the limited diffraction beams, the elements of two-dimensional arrays will be grouped into a number of rings, each of which will be driven with a different waveform. For linear scans of the limited diffraction beams, the annular rings will be shifted one element at a time in the scan direction (see Fig. 1(a)).

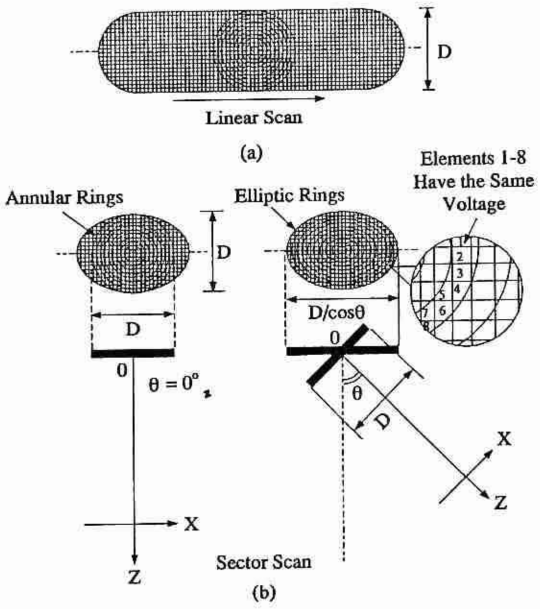

Fig. 1 Schematic diagrams for producing the limited diffraction beams with two-dimensional arrays. (a) Scanning the limited diffraction beams linearly by shifting the annular ring pattern one element a time along the scan direction. (b) Steering the limited diffraction beams in a sector format. The aperture of the array is compensated so that the projection of the aperture on a plane perpendicular to the beam axis is a constant annular ring pattern.

To steer the limited diffraction beams in sector format, the projection of the aperture of the two-dimensional array on a plane perpendicular to the beam axis must be a constant annular pattern (Fig. 1(b)), otherwise, the limited diffraction beams produced will have severe distortions (see next Section).

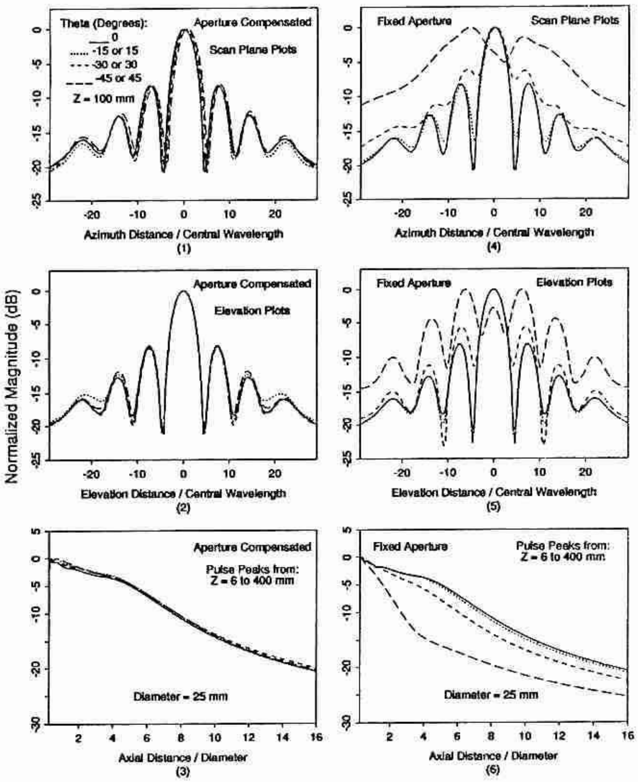

Fig. 2 Transverse and axial line plots of a J_0 Bessel beam. 14 rings are grouped from the two-dimensional array elements and 14 drive waveforms are used to produce the beam. Full lines, dotted lines, dashed lines and long dashed lines correspond to steering angles of 0°, ±15°, ±30°, and ±45°, respectively. Panels (1) to (3) are results when the aperture of the array is compensated so that its projection on the plane perpendicular to the beam axis is a constant annular ring pattern (aperture compensated). Panels (4) to (6) are the results when the ring pattern of the array is not compensated (fixed aperture). Panels (1) and (4) are transverse (perpendicular to beam axis) line plots of the maximum magnitudes of the beam in scan direction at a distance Z = 100 mm along the beam, while panels (2) and (5) are the plots in elevation direction. Panels (3) and (6) are peak magnitude of the beam along the beam axis from 6 to 400 mm away from the surface of the transducer.

III. SIMULATIONS AND RESULTS

The following will show line plots of simulated limited diffraction beams in a sector scan at several steering angles covering an arc of ±45° with and without the aperture compensation in the scan direction. For comparison, a Gaussian beam is also simulated.

In the simulation, a two-dimensional array with a central frequency of 3.5 MHz and a largest diameter of the projected annular ring pattern of 25 mm (projected to the plane perpendicular to the beam axis) is assumed. The -6 dB one-way bandwidth of the array is assumed to be about 82% of the central frequency and the size of the elements of the array is 0.64 mm × 0.64 mm (about $1.5\lambda \times 1.5\lambda$, where $\lambda = 0.43$ mm is the wavelength of the beams in water). 14 rings (annular or elliptic) are grouped from the array elements and each ring is driven by a different waveform. Linear delays are applied to the array elements in the scan direction to steer the beams. Discrete summation is used to replace the continuous integration of the Rayleigh-Sommerfeld formulation of diffraction [19] to calculate the beams.

The simulation results of a J_0 Bessel beam ($J_0(\alpha r)$, where $\alpha = 1.21751$ mm^{-1} is a scaling factor and r is a radial distance of the projected ring pattern) [6] steered by the two-dimensional array in a sector format are shown in Fig. 2. The beam is steered at 0°, ±15°, ±30°, and ±45°, respectively. The upper 4 panels show transverse line plots of the beam and the bottom two panels are the magnitudes of the beam along the beam axis. The transverse line plots are obtained by finding the maximum magnitudes of the beam in the direction of the beam axis and plotting them versus the transverse axes either in scan direction (Figs. 2(1) and 2(4)) or in elevation direction (Figs. 2(2) and 2(5)). The left panels of Fig. 2 represent the plots when the aperture of the array is compensated in the scan direction so that the projection of the ring patterns of the aperture on the plane perpendicular to the beam axis is a constant annular ring pattern. The right panels of Fig. 2 show the results of a fixed aperture ring pattern (not changed with the steering angle).

Figure 3 has the same format as that of Fig. 2. It shows the results of a zeroth-order X wave (the parameter of the X wave is $a_0 = 0.05$ mm and $\theta = 4°$) [8]. With the above parameters, the -6 dB beam width of the main lobes of the Bessel beam (Fig. 3) and the X wave (Fig. 4) will be about 2.5 mm and 2.8 mm, respectively. Figure 4 has also the same format as that of Fig. 2, but it represents the results for a focused Gaussian beam (FWHM—full width at half maximum is 12.5 mm and focal length is 100 mm).

IV. A SUGGESTED SECTOR SCAN SYSTEM

It is seen from the simulations above that the limited diffraction beams will have only small distortion if the change of the projection of the aperture of the array on the plane perpendicular to the beam axis is small (a few percent, see Figs. 2 to 4, where ±15° steering angles give a change of the projection of about ±3.5%). Therefore, to cover the steering angles from $-45°$ to $+45°$, only 4 ring patterns grouped from the array elements are required if the allowance of the change of the projection is ±5%.

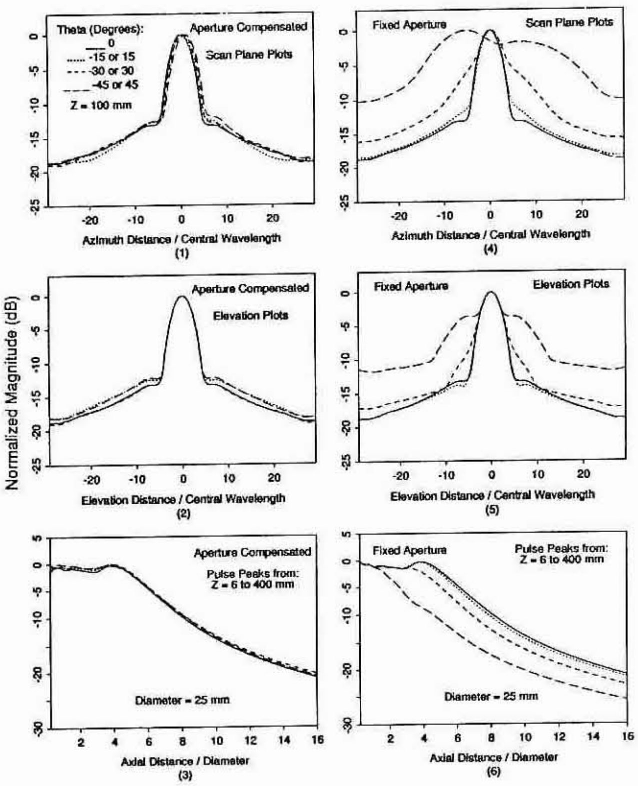

Fig. 3 The same as Fig. 2 except that a zeroth-order X wave is produced and steered by the two-dimensional array.

Figure 5 shows a suggested sector scan system for steering the limited diffraction beams. It uses 4 elliptic ring patterns to cover $-45°$ to $+45°$ beam steering. The 4 patterns are chosen to give a complete compensation at steering angles of ±18°, ±30°, ±37°, and ±43°, respectively. Each pattern covers ±5% change of the projection of the aperture on the plane perpendicular to the beam axis, i.e., the following steering ranges are covered, ±(0°~25°), ±(25°~34°), ±(34°~40°), and ±(40°~45°), respectively. A switching box is used to choose a pattern according to the steering angle. Before the array elements are grouped into the patterns, they are linearly delayed in the scan direction to steer the beams. Each pattern contains 14 rings which can be driven by 14 different waveforms or combined to one RF output by a dynamic focusing receive circuit.

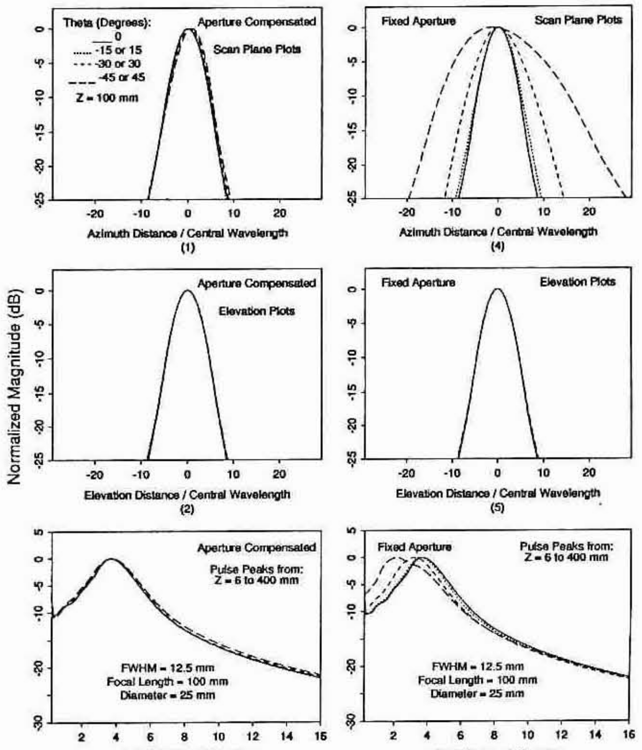

Fig. 4 The same as Fig. 2 except that a focused Gaussian beam is produced and steered by the two-dimensional array. The Gaussian beam is assumed to have a FWHM (full width at half maximum) of 12.5 mm and a focal length of 100 mm.

V. DISCUSSION

The simulation results (Figs. 2 to 4) show that with the compensation of the aperture of the transducer array, good limited diffraction beams can be produced. In contrast, the beams produced by the non-compensated aperture distort severely in both orthogonal directions at larger steering angles. This demonstrates that the limited diffraction beams are coupled between the orthogonal axes. For the conventional Gaussian beam (Fig. 4), the change of projection in the scan direction affects only the beam shape in the same direction (the focal length reduces as the projection area reduces or the curvature of the wave front increases). This means the Gaussian beam in the orthogonal directions is de-coupled.

The dimension of the elements of the two-dimensional array for producing limited diffraction beams depends on the wavelength of the beams and the smallest distance where the fields are observed as well as the spectra of the apodization functions on the transducer aperture. Smaller wavelength, shorter observation distance, or higher spatial frequency requires smaller element sizes.

The number of elements of a two-dimensional array required for steering the limited diffraction beams is usually large (about 1700 elements in the above example for steering angle from −45° to +45°). For linear scans, the number is even larger. However, the number of wires can be reduced by half because of the symmetry of the beams in the elevation direction. The large number of elements of the array make the wire connections and the associated electronic systems very complex (Fig. 5).

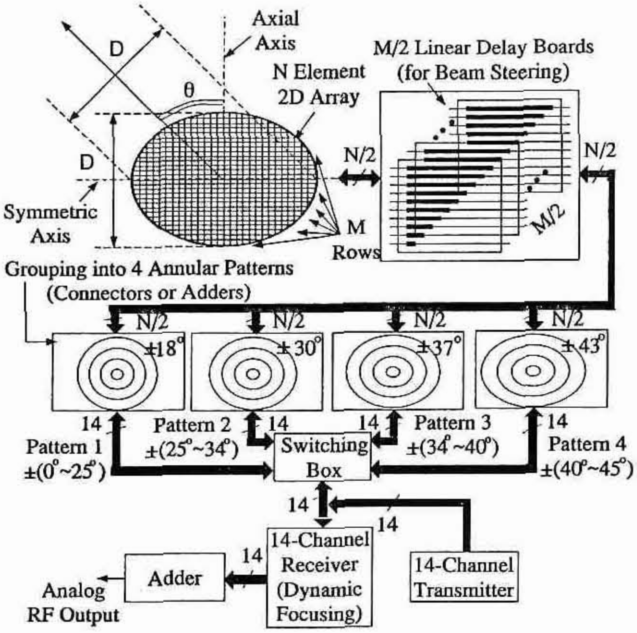

Fig. 5 Block diagram of electronic system for controlling the two-dimensional array to produce and steer the limited diffraction beams. The 14–channel transmitter provides 14 waveforms which are used to drive the conventional annular array to produce the limited diffraction beams. Through the switching box, the drive signals are sent to one of the ring patterns which is selected according to the steering angle of the beams. Each ring pattern covers a ±5% change of the projection of the aperture on a plane perpendicular to the beam axes, i.e., ±(0°∼25°), ±(25°∼34°), ±(34°∼40°), and ±(40°∼45°). The 4 patterns correspond to the beam steering at ±18°, ±30°, ±37°, and ±43°, respectively. Each pattern is linearly delayed before the waveforms are sent to the transducer elements to steer the beams. In receive, the signal flow direction is reversed and the conventional dynamic focusing is used.

The large number of array elements increases the possible cross-talk among the elements. To reduce the cross talk, PZT ceramics/polymer composite materials may be used to construct the array.

IV. CONCLUSION

Steering the axially symmetric limited diffraction beams with a two-dimensional array is feasible in principle if the size of the array elements are appropriately small and the aperture of the array is compensated so that the projection of the aperture on a plane perpendicular to the beam axis is a constant annular ring pattern as the beam steers.

If ±5% change of the projection of the aperture is allowed, only 4 elliptic ring patterns are required to cover a steering angle from −45° to +45° (total change of the projection of the aperture will be about 40%) to simplify the associated electronic system.

V. ACKNOWLEDGMENTS

The authors appreciate the secretarial assistance of Elaine C. Quarve and the graphic assistance of Julie M. Patterson. This work was supported in part by grants CA 43920 and CA54212–01 from the National Institutes of Health.

VI. REFERENCES

1. J. B. Brittingham, "Focus wave modes in homogeneous Maxwell's equations: transverse electric mode," J. Appl. Phys. 54(3):1179–1189, 1983.
2. R. W. Ziolkowski, D. K. Lewis, and B. D. Cook, "Evidence of localized wave transmission," Phys. Rev. Lett. 62(2):147–150, Jan. 9, 1989.
3. J. Durnin, J. J. Miceli, Jr., and J. H. Eberly, "Diffraction-free beams," Phys. Rev. Lett. 58(15):1499–1501, April 13, 1987.
4. D. K. Hsu, F. J. Margetan, and D. O. Thompson, "Bessel beam ultrasonic transducer: fabrication method and experimental results," Appl. Phys. Lett. 55(20):2066–2068, Nov. 13, 1989.
5. J. A. Campbell and S. Soloway, "Generation of a nondiffracting beam with frequency independent beam width," J. Acoust. Soc. Am. 88(5):2467–2477, Nov., 1990.
6. Jian-yu Lu and J. F. Greenleaf, "Ultrasonic nondiffracting transducer for medical imaging," IEEE Trans. UFFC 37(5):438–447, Sept., 1990.
7. Jian-yu Lu and J. F. Greenleaf, "Formation and propagation of limited diffraction beams," Acoustic Imaging, vol. 20, Ben-li Gu, ed. (20th International Symposium on Acoustic Imaging, Nanjing, China, Sept. 12–14, 1992) (to be published in 1993).
8. Jian-yu Lu, and J. F. Greenleaf, "Nondiffracting X waves—exact solutions to free-space scalar wave

equation and their finite aperture realizations," IEEE Trans. UFFC 39(1):19–31, Jan., 1992.

9. Jian-yu Lu and J. F. Greenleaf, "Experimental verification of nondiffracting X waves," IEEE Trans. UFFC 39(3):441–446, May, 1992.
10. Jian-yu Lu and J. F. Greenleaf, "Theory and acoustic experiments of nondiffracting X waves," IEEE 1991 Ultrasonics Symposium Proceedings, Lake Buena Vista, FL, 91CH3079-1 2:1155–1159, Dec. 8–11, 199.1
11. Jian-yu Lu and J. F. Greenleaf, "Pulse-echo imaging using a nondiffracting beam transducer," US Med. Biol. 17(3):265–281, May, 1991.
12. Jian-yu Lu and J. F. Greenleaf, "Sidelobe reduction of nondiffracting pulse-echo images by deconvolution," Ultrason. Imaging 14(2):203, April, 1992 (abs.).
13. Jian-yu Lu and J. F. Greenleaf, "Evaluation of a nondiffracting transducer for tissue characterization," IEEE 1990 Ultrasonics Symposium Proceedings, Honolulu, HI, 90CH2938-9 2:795–798, Dec. 4–7, 1990.
14. Jian-yu Lu and J. F. Greenleaf, "Nondestructive evaluation of materials with a J_0 Bessel transducer," Ultrason. Imaging 14(2):203–204, April, 1992 (abs.).
15. Jian-yu Lu and J. F. Greenleaf, "Limited diffraction beams and their applications for ultrasonic imaging and tissue characterization," New Developments in Ultrasonic Transducers and Transducer Systems, F. L. Lizzi, ed., [SPIE's 1992 International Symposium on Optical Applied Science and Engineering, San Diego, CA, July 19–24, 1992] (Invited paper, to be published).
16. D. H. Turnbull and F. S. Foster, "Beam steering with pulsed two-dimensional transducer array," IEEE Trans. UFFC 38(4):320–333, July, 1991.
17. M. G. Maginness, J. D. Plummer, W. L. Beaver, and J. D. Meindl, "State-of-the-art in two-dimensional transducer array technology," Med. Phys. 3:312–318, 1976.
18. J. D. Plummer, R. G. Swartz, M. G. Maginness, J. R. Beaudouin and J. D. Meindl, "Two-dimensional transmit/receive ceramic piezoelectric arrays: Construction and performance," IEEE Trans. Sonics Ultrason. SU-25:273–280, 1978.
19. J. W. Goodman, *Introduction to Fourier Optics.* New York, NY: McGraw-Hill, 1968, chs. 2–4.