PULSE-ECHO IMAGING WITH X WAVE

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INTRODUCTION

Limited diffraction beams have a large depth of field. They could have applications in medical imaging,[1,2] tissue characterization,[3] nondestructive evaluation (NDE) of materials,[4] Doppler velocity measurement,[5] as well as other areas such as optics[6] and electromagnetics.[7]

In this paper, we perform the first experimental study of pulse-echo imaging with a recently discovered X wave.[8] Results are compared to those of pulse-echo imaging with a Bessel beam[6] and a conventional focused Gaussian beam. It is shown that pulse-echo imaging with limited diffraction beams have a larger depth of field than that with a conventional focused beam.

THEORY

A limited diffraction beam in a three-dimensional space is given by

$$\Phi(x, y, z - c_1 t), \tag{1}$$

where Φ represents a wave and is a solution to the isotropic/homogeneous wave equation, x, y, and z are spatial variables in rectangular coordinates, t is time, c_1 is real and is the phase velocity of the wave, and $z - c_1 t$ is the propagation term. X waves,[8]

$$\Phi_{XBB_0} = \frac{a_0}{\sqrt{(r \sin \zeta)^2 + [a_0 - i \cos \zeta (z - c_1 t)]^2}}, \tag{2}$$

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and Bessel beams,[6]

$$\Phi_{J_0} = J_0(\alpha r) e^{i\beta(z - c_1 t)}, \tag{3}$$

have the form of Eq. (1), where $c_1 = c/\cos\zeta$ and $c_1 = \omega/\beta$ for Eq. (2) and Eq. (3), respectively, a_0, c, ζ, and α are constants, $r = \sqrt{x^2 + y^2}$ is a radial distance, J_0 is the zero-order Bessel function of the first kind, $\beta = \sqrt{(\omega/c)^2 - \alpha^2}$, and ω is an angular frequency.

EXPERIMENT

Because a limited diffraction beam has the same lateral beam profile at any axial distance, z, it can be constructed for $z > 0$ if it is produced at $z = 0$. Limited diffraction beams at $z = 0$ are given by

$$\Phi(x, y, z - c_1 t)|_{z=0}, \tag{4}$$

which is a function of t when observed at any transverse position, (x, y). If limited diffraction beams are rotary symmetric around the axis, such as those in Eqs. (2) and (3), they can be approximated with a stepwise function of r and can be approximately produced with an annular array. In this paper, we study only this case.

A block diagram of pulse-echo imaging using an X wave is shown in Fig. 1. A 13–element, 3.5 MHz central frequency, and 22.6 mm diameter ultrasonic annular array transducer was used to produce the X wave. Waveforms to drive the transducer were calculated from Eq. (2) with $z = 0$ at various radial distances that corresponded to the central radii of the transducer elements. Radio frequency (rf) echo signals were received by the same transducer and the outputs of the transducer elements were amplified and digitized. To obtain a B-mode image, the transducer was scanned linearly over an object to produce multiple A-lines. A modified AIUM standard 100 mm test object (Fig. 2) was used for the imaging study.

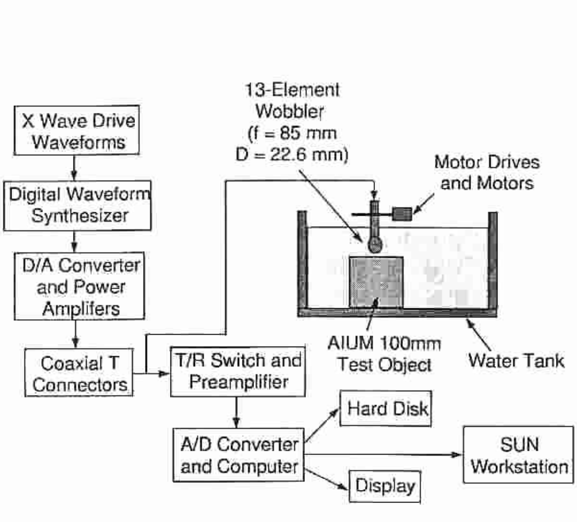

Figure 1. Block diagram of pulse-echo imaging with X wave.

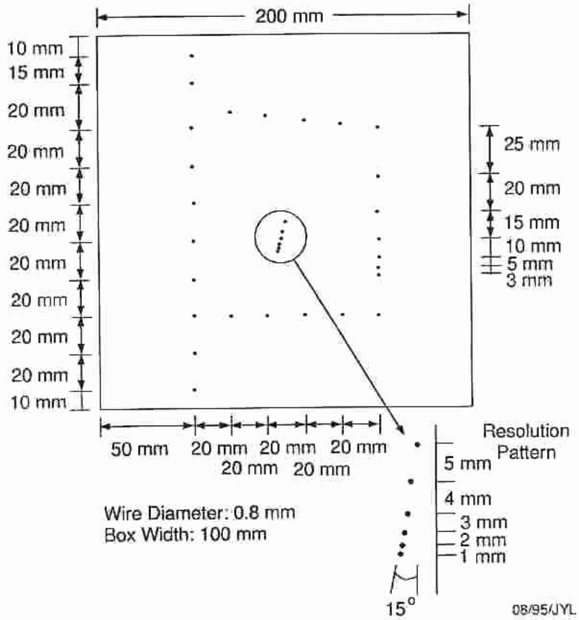

Figure 2. A cross section of a modified AIUM standard 100 mm test object. The object was obtained by adding four additional wires on top (two wires) and bottom (two wires) of the standard AIUM test object. The additional wires are useful for studying the large depth of field of limited diffraction beams.

To produce an X wave response in receive, rf data obtained from the transducer elements were filtered, summed, and then envelope detected. The impulse responses of the filters were calculated from Eq. (2) with $z = 0$ and $r = r_i$, where r_i was the central radius of the ith element (Fig. 3). Similarly, the same filters can also be used in transmit to replace the multichannel waveform synthesizer (Fig. 1) for producing drive waveforms (Fig. 3).

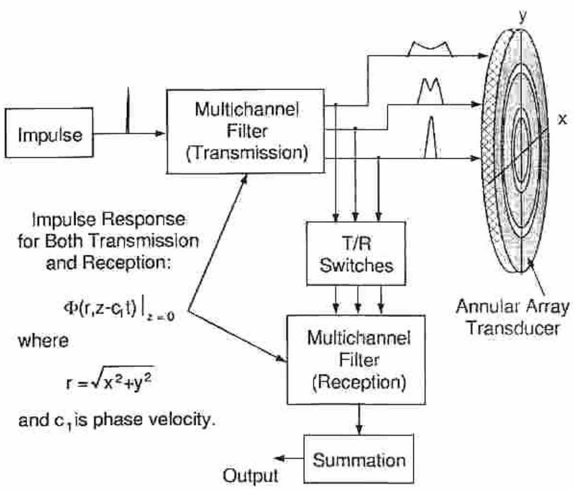

Figure 3. Filters for the X wave pulse-echo imaging system.

RESULTS

Experiment results for X wave pulse-echo imaging of the modified AIUM test object are shown in the left panel of Fig. 4. For comparison, pulse-echo images with a Bessel beam and a focused Gaussian beam are also shown. These images were obtained with the same conditions except that the transmit beams and the filters in receive were different. Parameters of these beams are the same as those in reference,[9] and are shown on the bottom of Fig. 4. For images obtained with the X wave and the Bessel beam, a dynamic aperture was used in receive to reduce sidelobes near the surface of the transducer. The size of aperture was increased from 5.46 mm (three elements) to 22.6 mm (13 elements) linearly as the axial distance where echoes returned was increased from 10.6 mm to 104.7 mm.

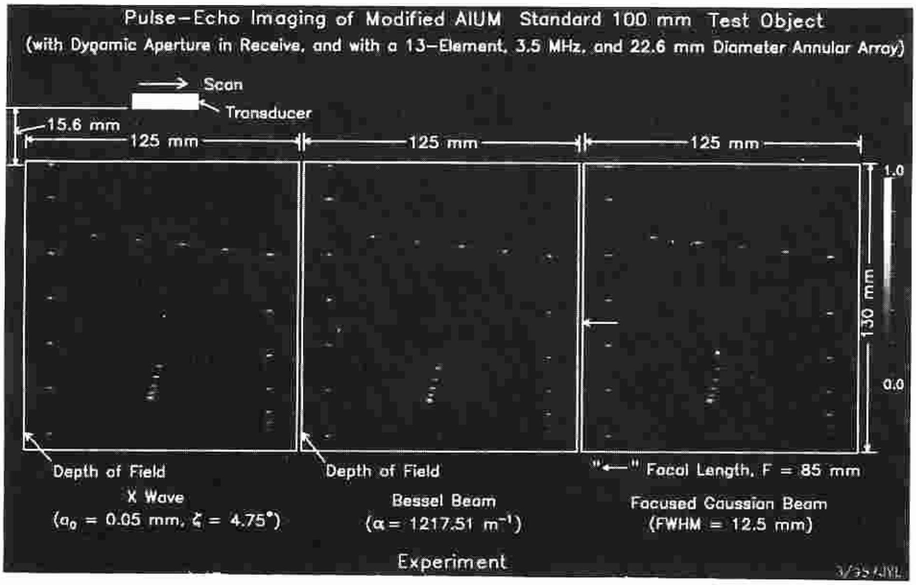

Figure 4. Pulse-echo images of the modified AIUM standard 100 mm test object with an X wave (left panel), Bessel beam (middle panel), and focused Gaussian beam (right panel).

To see clearly the lateral resolution at different axial distances, cross-sectional images of lines (line spread function or LSF) on the left-most column of each image in Fig. 4 were cut with a window of 24 mm (lateral) $\times$ 10 mm (vertical). The peak of each vertical line (A-line) of the image in the window was plotted versus the lateral distance (Fig. 5) to show the highest sidelobes of the LSF. The -6dB width of the LSF is shown in Panel (8) of Fig. 5 as a function of the axial distance from 0 to 200 mm. The depth of field for both the X wave and the Bessel beam is about 136 mm that is indicated by a vertical line (Panel (8) of Fig. 5).

DISCUSSION

From the experiment results (Figs. 4 and 5), one sees that the pulse-echo images obtained with limited diffraction beams have a larger depth of field but have higher sidelobes than those obtained with a conventional focused Gaussian beam. It is noted that the sidelobes shown in Fig. 5 are that of the LSFs and are much higher than those of point spread functions (PSFs). The results also show that the −6dB width of the LSF of the X wave is larger than that of the Bessel beam in the depth of field (136 mm). This is because the actual central frequency of the transducer is about 2.9 MHz instead of 3.5 MHz indicated by the manufacturer[1]. For Bessel beams, the change of central frequency will not affect the −6dB beam width that is determined by the width of the central lobe of the Bessel function. For conventional focused Gaussian beams, the −6dB beam width is determined by the apodization of aperture, the f-number, as well as the central frequency. It is seen that the variation of the width of the LSF over distance is the largest for the focused Gaussian beam (Panel (8) of Fig. 5) that has an f-number of about 3.76 (focal length is 85 mm) and a full width at half maximum (FWHM) of about 12.5 mm at the surface of transducer.

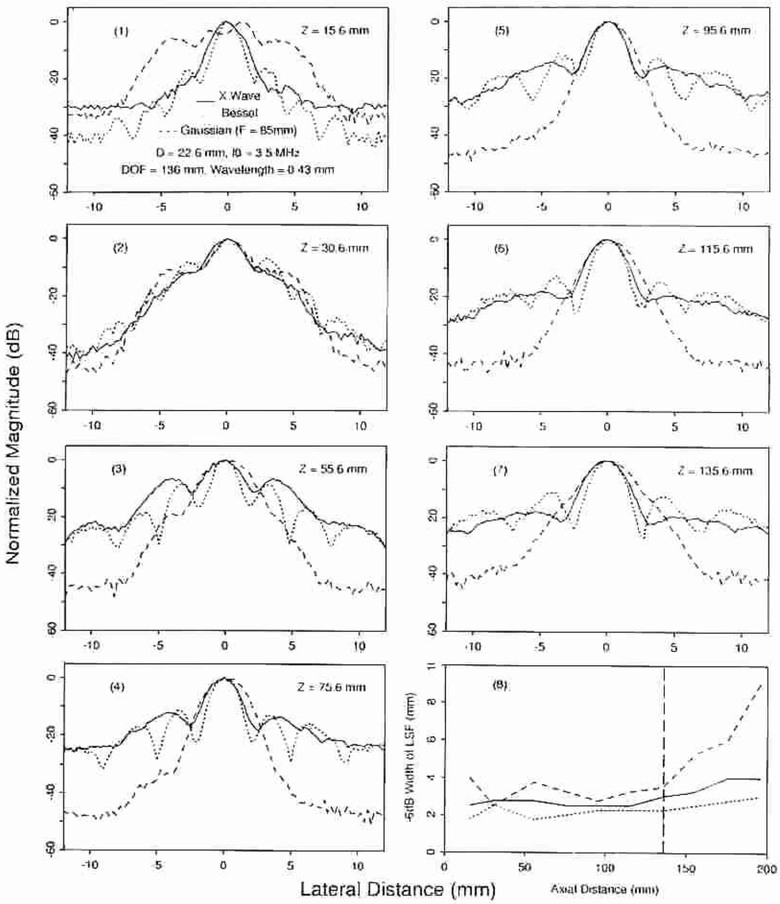

Figure 5. Line spread functions (LSF) of the pulse-echo imaging systems with the X wave (full lines), Bessel beam (dotted lines), and focused Gaussian beam (dashed lines) at several axial distances, z = 15.6 mm (Panel (1)), 30.6 mm (Panel (2)), 55.6 mm (Panel (3)), 75.6 mm (Panel (4)), 95.6 mm (Panel (5)), 115.6 mm (Panel (6)), and 135.6 mm (Panel (7)). The −6dB width of the LSF versus the axial distances is shown in Panel (8) where the vertical line (long dashed line) indicates the depth of field of the X wave and the Bessel beam.

[1] Echo Ultrasound, Reedsville, PA, U.S.A.

Theoretically, beam width of limited diffraction beams should be constant over a large distance (large depth of field). The fluctuation of the width of the LSFs in Panel (8) of Fig. 5 could be caused by several factors in our experiment. For example, the transducer is not rotary symmetric; the curvature (85 mm) of transducer can not be completely compensated because each element has a certain width; the transfer function, bandwidth, and the central frequency of each element is different from each other; the weightings may deviate from theoretical values due to the variation of sensitivity from element to element. In addition, the plastic cap (wobbler cap) that is in front of the transducer may also cause some distortion.

CONCLUSION

We have successfully produced a pulse-echo image with an X wave. Like Bessel beams, X waves have a large depth of field but higher sidelobes as compared to conventional focused beams. However, sidelobes of limited diffraction beams can be reduced by various methods.[10]

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