PRODUCTION OF A DIFFRACTIONLESS ULTRASONIC BEAM

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INTRODUCTION

The propagation of ultrasonic beams is a phenomenon of widespread interest to a variety of technologies including sonar, medical ultrasound, and nondestructive evaluation. One goal in most applications is the production of a narrow, highly collimated beam of sound. Rigid piston radiators have often been employed and have been thoroughly analyzed. This type of source has the generally undesirable attributes of a complicated near field interference structure as well as far field side lobes. Sources which produce a Gaussian amplitude distribution have been studied since, for this case, the previous disadvantages are eliminated. Unfortunately, Gaussian radiators are more difficult to manufacture [1,2]. Various types of focusing probes have also been analyzed for concentrating the sound in a narrow band over a short depth of field. Conically focussed, or axicon, probes have been examined for the purpose of extending the focal region for resolution over a greater depth of field. One disadvantage common to all of the above sources, and indeed to any physically realizable source, is the phenomenon of beam spread due to diffraction.

Recently, in the optics literature, Durnin [3,4] has pointed out the existence of an axially symmetric harmonic solution to the scalar wave equation in the form of a transverse Bessel function modulated by an axially varying phase, \( \phi(r,z) = J_0(\alpha r)\exp(j\beta z) \), where \( k^2 = \alpha^2 + \beta^2 \), and \( k \) is the wave number. When \( \alpha = 0 \), this is just a plane wave solution. However, for \( 0 < \alpha < k \), we have a forward propagating field which has a beam-like transverse profile that does not vary with axial position, and is therefore diffractionless. The beam energy is not localized, however, but is instead infinite due to \( J_0 \) not being square integrable. Durnin analyzed a finite
aperture approximation to a \( J_0 \) beam for the optical case and has shown both analytically and experimentally that a beam may be produced which can have a small spot size while retaining a significant depth of field over which the transverse profile is approximately constant. Initial attempts to produce a diffractionless acoustic beam have been reported by other investigators [5-7]. These have employed transducer arrays or transducer disks with radially varying poling or excitation. In this paper, we discuss an approach for the acoustic case analogous to the method of Durnin and report the experimental generation of a nondiffracting \( J_0 \) Bessel beam. We also will discuss the potential for constructing a practical transducer via this approach.

![Figure 1. Experimental setup for producing diffractionless ultrasonic beam.](image)

**EXPERIMENT**

If the Bessel function solution is decomposed into an angular spectrum of plane waves, we find that the only wave vectors which contribute lie on the surface of a cone centered about the z axis and making an angle \( \theta = \arcsin(a/k) \) with it. Durnin showed, for the optical case, that this plane wave spectrum can be generated by a construction similar to that shown in Fig. 1, which is for the current acoustical case. A circular PZT piston transducer of radius \( a \) is used as the source. The center of the transducer disk is blocked by a circular disk of radius \( b < a \) made of a highly attenuative material (in this case, polystyrene). The resulting effective source is a thin annulus.
An acoustically convergent lens of focal length \( F \) and
diameter \( 2R \) is placed a distance \( F \) in front of the
transducer. Each point on the ring radiates a spherical wave
which the lens transforms into a plane wave traveling at
angle \( \theta = \arctan(a/F) \) relative to the \( z \) axis. Summing
contributions from each point on the ring yields the conical
set of wave vectors necessary for a Bessel beam with width
parameter \( \alpha = (ka/F) \left( 1 + a^2/F^2 \right)^{-1/2} \). If \( a \ll F \), then \( \alpha = ka/F. \) The
maximum possible depth of field is \( z_{\text{max}} = R/\tan\theta = RF/a. \) Past
this point, a shadow zone is produced due to the finite lens
aperture.

A 0.25 inch radius, broadband transducer was used as the
source. The blocking disk had a 0.22 inch radius. The lens
was a 1.0 inch radius, fused quartz plano-concave which has
an acoustical focal length of 6.85 inch in water. For
measurement of the generated sound field, a 0.75 inch focal
length, 0.25 inch radius transducer was scanned in a 2-D grid
perpendicular to the beam axis. The focal spot of the
receiver was much smaller that the Bessel beam width so that
the measured amplitude profile should closely represent the
actual Bessel beam profile at the axial distance
corresponding to the focal point of the receiver.

The received rf waveform at each point in the scan grid
was recorded and Fourier transformed to obtain the frequency
spectrum. The amplitudes at particular frequency values were
extracted for each point and plotted versus position in the
scan grid, resulting in images of the transverse beam
profiles at different frequencies and axial positions.

Figure 2a shows the data along a slice through the peak
of the sound field transverse to the beam axis at 3 MHz, at
an axial distance of \( z = 0.5 \) inch past the lens. Also plotted
is a \( J_0 \) function with \( \alpha = 10.4/\text{inch} \). This value of \( \alpha \), which
gives a best fit to the data, corresponds to a ring radius of
0.224 inch, approximately the inner radius of the annulus.
For comparison, a Gaussian beam with the same \( 1/e \) width as
the the main lobe of the Bessel function is also plotted
(\( w = 0.17 \) inch).

Figures 2b-d show the beam profile at distances of \( z = 10, 
15, \) and \( 17.5 \) inches past the lens. The theoretical Bessel
function has been scaled down at each axial distance to
account for sound attenuation in water. It is apparent that
the Bessel beam retains its initial width and amplitude to
about 17.5 inches, although the side lobe structure has
decayed. At 20 inches, which is not shown, the main lobe has
broken down. The ideal \( z_{\text{max}} \) for this case is 27.4 inches.
At 17.5 inches, the Gaussian beam has decreased by
approximately 80% from its initial amplitude. The Rayleigh
range for the Gaussian is \( z_R = \pi w^2/l = 4.6 \) inch. The Bessel beam
has propagated more than 3 times this distance without
significant diffraction loss.
Because the source is a finite width annulus rather than an infinitesimal ring, a range of source radii contribute to the beam field, each producing a slightly different beam width parameter $\alpha$. Since the phase parameter $\beta$ varies with $\alpha$, the wave becomes dispersive when the source has a finite width. This contributes to the breakdown of the Bessel profile before the ideal $z_{\text{max}}$ is reached.

The above results are quite exciting, although one disadvantage of the Bessel beam for the monochromatic case is the large magnitude of the side lobes. The beam is found to also be nondiffracting for the pulsed case. Figures 3a-d show the 2-D transverse profile scans of the peak-to-peak voltage of the rf waveform at various distances from the lens. The pulsed beam is actually somewhat narrower than the 3 MHz case due to the contribution of higher frequencies. Also, the pulsed beam displays no sidelobes due to incoherent addition of the sidelobes at the different frequencies. Since ultrasonic scanning is often done in the pulsed mode, this shows promise for having a narrow, sharply peaked interrogating beam with a large depth of field.
DISCUSSION

These results suggest that current ultrasonic transducer beam types can be greatly improved upon by the implementation of the diffractionless Bessel beam idea. The apparatus illustrated in Fig. 1, however, was contrived for the purpose of demonstrating the concept and is clearly not a practical one for ultrasonic inspection. However, it may be possible to construct a Bessel beam transducer by appropriately constructing a transducer element and lens combination. The manufacture should not be very different from that of a conventional focussed probe.

A proposed configuration is shown in Fig. 4. In this case, an annular transducer element is mounted on the planar surface of a thick plano-concave lens. The parameters such as annular radius and width, lens thickness, lens diameter, and lens radius of curvature must be chosen using thick lens theory to ensure that the annulus rests at the focal depth of the lens and that the desired characteristics of the beam are achieved. Further work on this subject will include the construction and testing of this transducer configuration.
Figure 4. Proposed configuration for Bessel beam transducer.

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