

## RECENT DEVELOPMENTS IN AXICON IMAGING

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## INTRODUCTION

In the formation of ultrasound images for medical diagnostic purposes, it has been recognized that some considerable improvement in image quality is possible in principle through the use of wide aperture imaging devices. Merely increasing the aperture of a single spherically focussed source, however, results in a reduction of the range over which good lateral resolution is maintained. Focal scanning, either by switching between multiple fixed-focus sources (Dick et al., 1979) or by the electronically-phased focussing of a multiple-element source (Melton and Thurstone, 1978; Arditi et al., 1982), has been exploited to overcome this problem, which is particularly important when imaging the female breast. Synthetic aperture (computer reconstruction) techniques also aim to solve this problem, though perhaps in a more versatile way (see the section on reconstruction tomography in this volume). An alternative scheme has been, by physical means, to provide a wave front which simultaneously converges towards all points down the imaging axis. The name axicon has been applied to this system, which was introduced as a new optical element by McLeod (1954) and is now well known in optics. The principle of generating a line focus in this way was utilized in the "scatter scanners" of Foster et al., (1980), so named because a separate receiving transducer was aimed along the focal line to collect ultrasound scattered at angles other than  $180^\circ$ . Considerable promise was shown by a system consisting of a  $45^\circ$  cone transmitter and an  $f5.4^\pm$  receiver (Foster et al., 1981), which generated a lateral point response with a full width half maximum (FWHM) that remained about  $0.7\lambda^\pm$  over a 5 cm depth of field. Very

$\pm$  The "f-number" is the ratio focal length/aperture diameter.  $\lambda$  is the wavelength of sound.

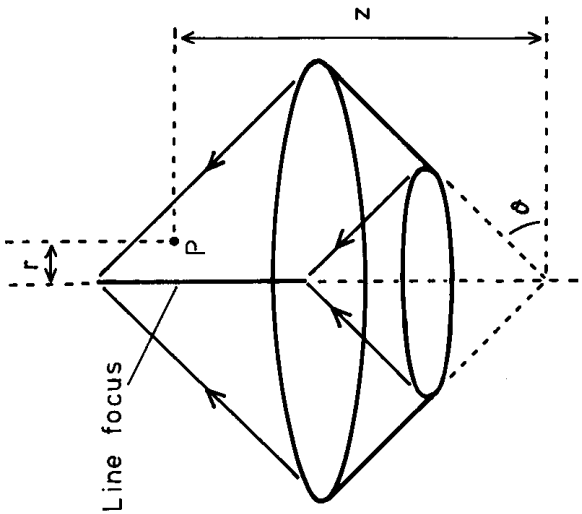


Fig. 1. Schematic diagram of a conically converging wave front showing the coordinate system for defining a field point  $P$ , and the convergence angle  $\theta$ .

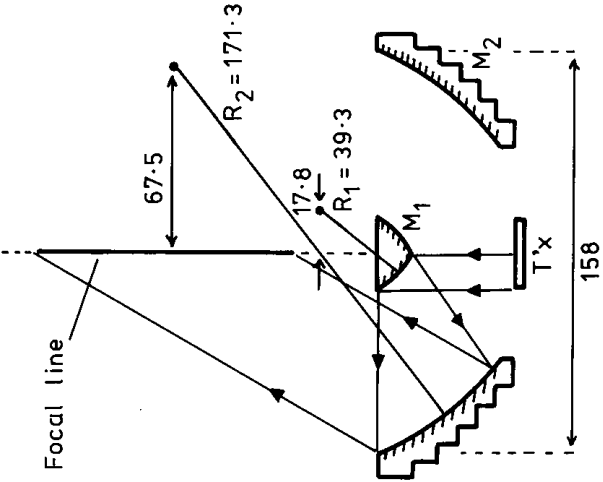


Fig. 2. Schematic diagram of the mirrors,  $M_1$  and  $M_2$ , used in the present experiment. Dimensions shown are in mm,  $R_1$  and  $R_2$  are the radii of curvature of mirrors  $M_1$  and  $M_2$  respectively.

high quality images of excised breast tissue were demonstrated at a frequency of 4 MHz.

Axicons represent a family of devices which are figures of revolution and from which rays converge towards a common focal line on the axis of revolution. A variety of methods are in principle available for fabricating acoustic axicon sources, including the shaped piezoelectric plastic sheet used by Foster et al. (1981), a single annular transducer (Burckhardt et al., 1975; Weight and Brown, 1982) or phased annular arrays. Existing plane or other-shaped waves might also be converted to axicon form by systems of lenses, diffraction gratings or mirrors; all of which have been used in optical axicons. In an experimental ultrasound axicon Burckhardt et al. (1973) used a single plane transducer followed by a strongly focussing perspex lens and a small conical reflector, placed beyond the focal point of the lens, to spread the sound beam onto a large converging reflector which then formed the conical wave front returning to the axis. Using the same system for both transmission and reception encouraging results were achieved, but the attempt to focus over a depth range of some 20 cm using a convergence angle of only  $7^\circ$  meant that a lateral resolution of about  $3\lambda$  only was attained. For the present work it was decided to build as simple an axicon mirror system as possible, having a large convergence angle and having the particular feature of utilizing existing B-scan equipment and transducers as the sound source and receiver. The time available for this study was limited, so that the necessary investigations of the physical characteristics, limitations and tolerance of the system were only preliminary.

## THEORY

The relevant continuous wave theory, to a good first approximation for small values of the convergence angle and for points close to the axis, was given for the optical axicon by Fujiwara (1962) and was later refined by Lit and Brannen (1970). Patterson and Foster (1981) have recently provided a more complete analysis for conical acoustic radiators through the impulse response approach. Fujiwara's approximate expression for the axicon intensity distribution  $I(r,z)$ , which we shall use as an approximate representation of the pulse-echo signal amplitude for a point target, may be written in terms of the geometrical parameters shown in Fig. 1 as

$$I_{\text{axicon}} = C_1 \frac{\sin^2 \theta}{\lambda z} J_0^2(kr \sin \theta) \quad (1)$$

where  $C_1$  is a constant,  $k = 2\pi/\lambda$  and  $J_0$  is the Bessel function of order zero. This is actually the result for a toroidal wavefront, but it differs from that for the cone only in the value of the constant and in that the on-axis intensity,  $I_0$ , falls off inversely with distance,  $z$ , whereas for the cone  $I_0$  is directly proportional to  $z$ . The latter distribution is in fact the more useful one for imaging in an attenuating medium.

An essential feature of Equ. 1 is that the  $J_0^2$  function is constant with  $z$ , i.e. the lateral resolution is independent of distance within the focal zone. The intensity falls off initially very rapidly with the off-axis position,  $r$ , the rate of fall off depending strongly on the convergence angle for small values of  $\theta$ , but not so strongly for large angles. In particular, for  $\theta \gtrsim 30^\circ$  the improvement in lateral resolution due to increasing  $\theta$  becomes much less marked. The lateral resolution of the axicon is defined by

$$\text{FWHM}_{\text{axicon}} \approx \frac{0.41 \lambda}{\sin \theta} \quad (2)$$

This rapid fall off is followed by a series of diffraction minima and maxima. These define the side lobes of the device which are somewhat smeared to form a "skirt" to the lateral resolution curve in pulsed operation. For comparison, the intensity profile in the plane of focus of a spherically converging wave is

$$I_{\text{sphere}} = C_2 \frac{J_1^2(kr \sin \theta)}{(kr \sin \theta)^2} \quad (3)$$

where  $J_1$  is the Bessel function of the first order. The lateral resolution is then given by

$$\text{FWHM}_{\text{sphere}} \approx \frac{0.55 \lambda}{\sin \theta} \quad (4)$$

Thus the resolution of the axicon is somewhat better, for a given aperture, than in the conventional focussing process. However, about 84% of the total power is contained within the main peak of Equ. 3 whereas the majority of the power in an axicon wave is carried in the side lobe regions. The  $J_0^2$  function has a  $1/r$  envelope for large values of the argument and the envelope of the function on the right of Equ. 3 varies as  $1/r^3$ . The axicon should therefore be useful for imaging an object composed of a few discrete points, but it is anticipated that when used within an extended scattering object the strong off-axis contributions will lead to a loss of imaging contrast, i.e. it could be said that the axicon system suffers from an inherently poor dynamic range.

As pointed out by Clarke (1981), multiple reflections within a sound beam may contribute additional (incoherent) noise to the image, which is a function of the effective beam diameter. The low  $f$ -number devices under discussion have very wide beams and so the signal-to-incoherent noise ratio is expected to be less than for a conventional system. Furthermore, since only a fraction of the total power in the wave is used to form the image of a given object point, we expect a lower sensitivity to point targets but a high sensitivity to large interfaces of a similar shape to the wavefront.

## MIRROR DESIGN AND CONSTRUCTION

The geometrical design used for the mirrors (Fig. 2) is simple and offers considerable flexibility; the detailed parameters of a particular system may be chosen to accommodate a large variety of plane or focussed transducers, cone apertures, convergence angles and focal depths. The two mirror surfaces are each a figure of revolution derived from the rotation of a segment of a circle around the acoustic axis, but with the centre of curvature of the mirrors located as shown offset from the acoustic axis. Mirror  $M_1$  causes the wave from the transducer to diverge in the plane of the figure, with rotational symmetry about the acoustic axis, and  $M_2$  changes this diverging wave front to the conical form required.

A prototype system was designed with the application of breast scanning (with the patient lying in the prone position) in mind. It was decided to use plane transducers, and to fix the depth of focus and convergence angles at 10 cm and  $30^\circ$  respectively. With these parameters and the diameter of the transducer fixed, the dimensions of the mirrors shown are readily derived. It was assumed in this design that the small mirror is located in the far field of the transducer and that the wave from the transducer is plane. In fact, when used, the system was found not to be very sensitive to variations in the distance between the transducer and the small mirror.

The mirrors were made of brass, with the surfaces polished to an optical finish. Tolerances on radii were about 0.1 mm, where possible. Relative positioning was achieved by cutting the final surfaces after assembly. The system was so made that it could be used in the tank being developed for breast scanning, with any one of several standard transducers. The mirrors could be readily dismantled so that the breast scanner could be used in its normal mode for direct comparison. The mirrors are shown in Fig. 3, and again schematically, mounted in the breast tank, in Fig. 4.

## RESULTS

Tests of the system were carried out with a 3.7 MHz, 7.5 mm diameter plane transducer having a pulse length of about 3 cycles, and a 3.6 MHz, 40 mm diameter bowl transducer focussed at 145 mm and having a pulse length of about 6 cycles. Fig. 5a shows the ray plot for the former of these transducers. In spite of the fact that the mirrors were not designed to be used with a focussed input wave the ray plot of Fig. 5b suggests that quite good conical wave fronts might still be expected from this arrangement. For both arrangements a 0.3 mm diameter nylon filament was scanned at various positions within the expected focal range by linear translation of the complete mirror/transducer assembly. Examples of the resulting lateral pulse-echo profiles, obtained in the manner described by Bamber and Phelps (1977), are provided in Figs 6a and 6b. Many of

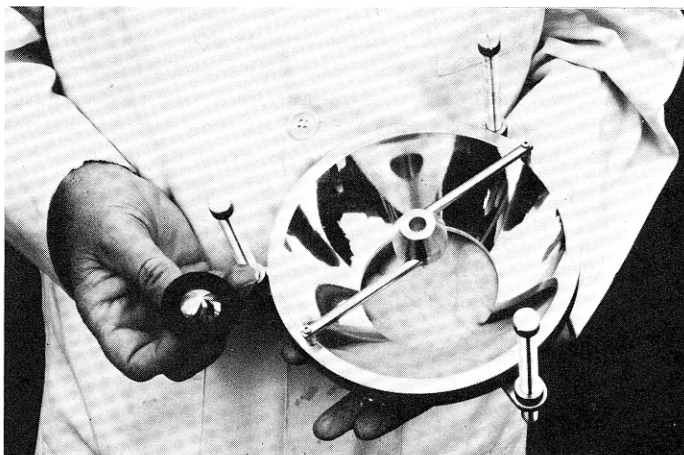


Fig. 3. The subassembly of the mirrors used showing  $M_1$  on the left with a rubber aperture stop in place, and  $M_2$  on the right with the screws used for adjusting the orientation with respect to the incoming sound beam.

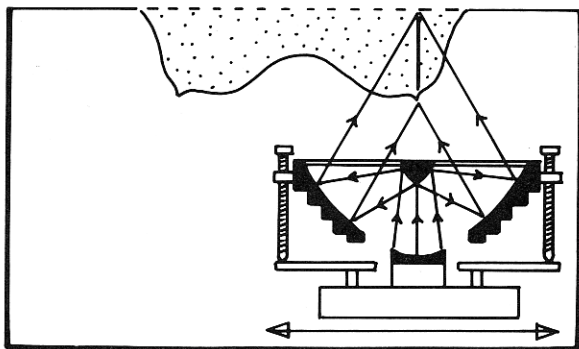


Fig. 4. Schematic diagram illustrating the proposed manner of use of the mirrors in the breast scanning tank.

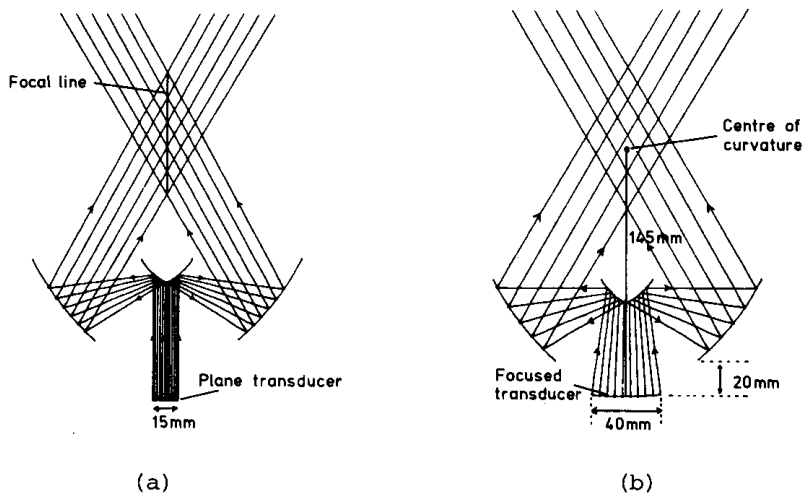


Fig. 5. Computer ray plots for the mirror system in use with a plane transducer (a) and a focussed bowl (b).

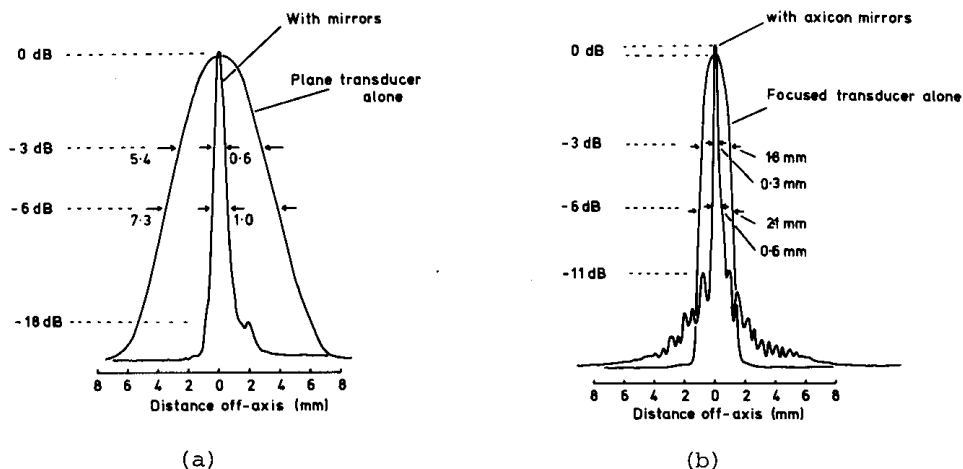


Fig. 6. Lateral pulse-echo profiles for a line target corresponding to the arrangements (a) and (b) in Fig. 5. Positional accuracy was  $\pm 0.1$  mm and the axial distance for the target in (b) was 158 mm.

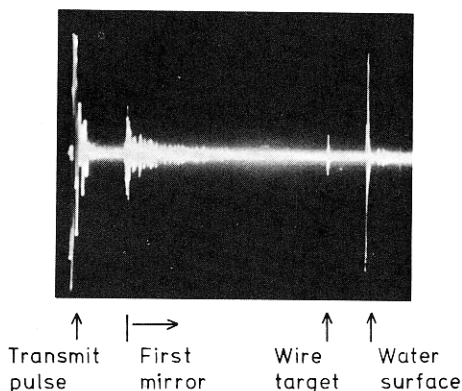


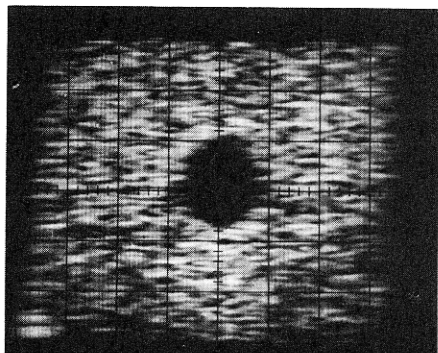
Fig. 7. A-scan from the axicon. The reverberations from the interior of the mirrors are clearly visible.

these plots were not completely symmetrical; this is presumed to be due to lack of perfect alignment between all the components of the system (including the target). It may be seen that over the central region a resolution ( $-6$  dB width, which is the FWHM) of about  $1.4\lambda$  was achieved (Equ. 2 would predict  $0.85\lambda$  for a point target). As expected, smoothed side lobes and high intensity levels far from the central maximum were also observed. The use of a line, rather than a point, target tends to emphasize this region and to broaden the maximum.

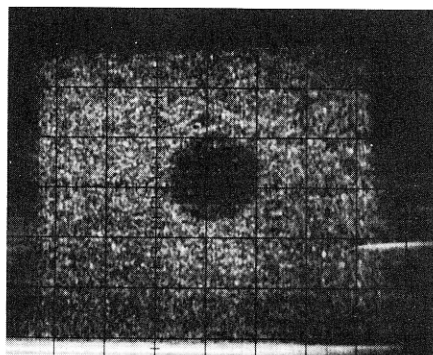
Although, as expected, the sensitivity (i.e. echo height) does not drop off rapidly with distance down the axis, spurious reflections, arising predominantly from reverberations within mirror  $M_1$ , interfered with the ability to make detailed measurements over a large part of the expected focal region. These are clearly visible in the A-scan in Fig. 7. It was possible to note, however, that the full width at the  $-3$  dB level remained approximately constant for at least 10 cm of range.

The images presented in Figs 8 and 9 are the results of scanning a piece of ordinary cellulose "sponge", which had been thoroughly degassed and had a hole, approximately 18 mm diameter, cut in it. This particular type of sponge has a wide range of sizes of cells ( $\sim 0.05$  to 3 mm) which can act as scattering structures. It will be seen from the figures that images of good quality are possible with the axicon mirror system. The improvement in image quality, over that obtained using the conventional transducers, is largely due to the reduced "speckle", which is a consequence of the large aperture of the axicon. The lateral resolution is clearly much improved



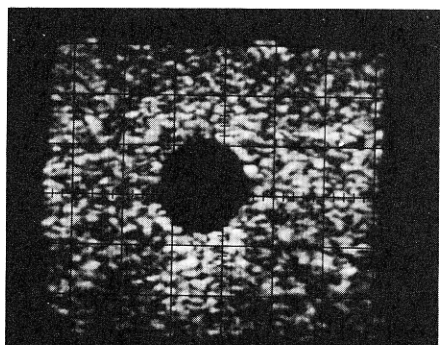


(a)

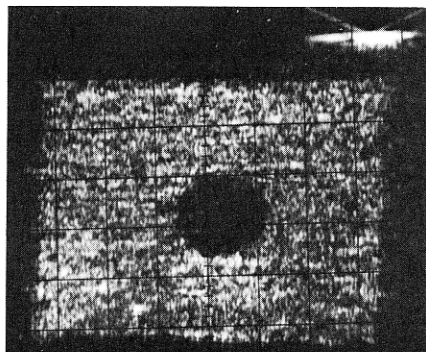


(b)

Fig. 8. B-scans of the cellulose sponge taken with the plane transducer alone (a), and then with the mirrors in place (b). For the conventional image (a) the graticule is calibrated 1 cm/div. The sponge was scanned left-right and the direction of sound propagation is top to bottom.



(a)



(b)

Fig. 9. As for Fig. 8 but the images were created with the focussed transducer alone (a), and with the focussed transducer plus the axicon mirrors (b). The section on results contains the transducer details.

but the speckle will also tend to be smoothed somewhat by an averaging of the returned pressure impulse over a range of scattering angles, from  $180^{\circ}$  to  $120^{\circ}$ . It is interesting that the effective beam width has been reduced so much that for Fig. 9b, where the sound pulse is fairly long, the streaks which make up the speckle pattern are in the axial direction rather than the lateral direction which is more usual. Note also that, whereas the image quality falls off with distance in 8a and 9a, it is constant with depth in 8b and 9b.

Figs 8 and 9 also demonstrate very well the trade-off between point resolution and image contrast predicted by the axicon theory. In the top right corner of Fig. 9b there appears a prominent star shaped artefact which is known to arise from the strong reflection off the wire frame used to support the sponge. The star shape is a direct consequence of the conical shape of the wavefront and the relatively high level of the skirts of the resolution curve of Fig. 6. Presumably all parts of the axicon images have this star pattern associated with them but only in the case of strongly reflecting point objects is the pattern visible. For a distributed scattering object like the sponge the result is a general reduction of image contrast between the sponge and the 18 mm hole, as compared to the images made using the conventional transducers. Additional artefacts present in Figs 8b and 9b, seen as a faint series of lines crossing the images, are due to the mirror reverberations described earlier.

The sensitivity of the mirror system, judged by the ratio of the echo amplitude for a target at a given position to the amplitude of the same echo using the same transducer without the mirrors in place, was seen to vary with the shape of the target and with the transducer used. For the sponge echoes the mirror sensitivity was -15 dB when the focussed transducer was used and -6 dB with the plane transducer. A plane perspex surface placed normal to the beam at the focal plane of the focussed transducer, however, yielded a mirror sensitivity of about -7 dB.

## CONCLUSIONS

The potential for high resolution over a large depth of focus and excellent reduction of the coherent speckle artefact has been shown to apply as well as can be expected in the presence of the artefacts and noise inherent in the present form of axicon. The system of mirrors used to produce the wide aperture conical wave is both simple and highly flexible; mirrors may be designed for almost any convergence angle or depth of focus, and for use with most easily available B-scanning transducers.

The present low sensitivity and noise due to reverberations in the mirrors have prevented us from obtaining clinically useful breast images. Nevertheless, the results of scanning volunteers have

demonstrated most of the features mentioned above. Clearly, however, for the device to realize its potential usefulness the difficulties already discussed must be overcome. The reverberation noise can be reduced by making the back surfaces of the mirrors non-reflecting. Preliminary experiments have shown that a random pattern of small holes drilled in the back face, or backing the mirrors with lead, can be successful in this regard. A better choice of reflector material must be considered, which may also help to improve the sensitivity.

The star artefacts and poor imaging dynamic range associated with the high skirt (i.e. side lobe) level may prove more difficult to overcome. It is likely that some form of computer image treatment would enable the obvious star-shaped artefacts to be removed, but the poor contrast for distributed scattering media seems to be a sort of fundamental limitation of the axicon and may be serious. At present it seems sensible to limit the depth of focus, and hence the width of the conical beam, as much as possible. One method of achieving this in a variable manner is to use a transducer divided into annular zones which can be actuated individually or together in any combination. Some form of compromise between the width of the central peak and the height of the skirt, such as the use of a separate focussed receiver as suggested by Patterson and Foster (1981), may ultimately be necessary. It also seems likely that, for best results, it will be found that a particular design of axicon will be needed for each target organ.

It has been commented that, at least for the particular application of breast imaging, refraction at the tissue surface may degrade the image quality considerably. The results taken up to the present do not give any clear indication of how serious this problem will be, but it may constitute a further limitation on the resolution and depth of focus achievable.

Finally, we conclude that, in spite of some problems, the axicon principle has great potential for ultrasound imaging, and well merits further development. The original organ of interest, the breast, remains a most promising region for investigation.

#### ACKNOWLEDGEMENTS

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