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ATOMIC ENERGY
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L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

ACOUSTIC LENSES – FOCUSING IN ON DEFECTS

Lentilles acoustiques – Focalisation sur les défauts

C.A. KITTMER

Presented at the International Conference on Pipeline Inspection in Edmonton Alberta, 1983 June 13 - 16.

Chalk River Nuclear Laboratories   Laboratoires nucléaires de Chalk River

Chalk River, Ontario

March 1983 mars

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Special Projects Division
Chalk River Nuclear Laboratories
CHALK RIVER, Ontario K0J 1J0
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Résumé

Les lentilles acoustiques focalisent les ultrasons et engendrent des faisceaux étroits à champ proche réduit. Lorsqu'on les adapte à des transducteurs de type classique (à face plate) ces lentilles améliorent beaucoup l'aptitude à détecter les défauts et à juger de leur ampleur. Le présent rapport décrit un programme mis au point pour concevoir les lentilles acoustiques destinées aux inspections faites par contact ou par immersion. Ces lentilles peuvent avoir un mode de faisceau normal ou angulaire, les cibles étant plates ou incurvées. Les surfaces des lentilles ont une géométrie circulaire pour faciliter leur usinage. Pour l'inspection par faisceaux normaux des plaques plates, on se sert de lentilles sphériques ou cylindriques. Pour les inspections par faisceaux angulaires ou pour inspecter des surfaces incurvées, il faut avoir recours à une lentille composite afin de corriger l'aberration induite additionnelle. Il existe une telle lentille asphérique, ayant un rayon de courbure dans le plan d'incidence et un rayon de courbure différent dans le plan perpendiculaire au plan incident. Le profil de faisceau qui en résulte (à savoir l'emplacement du foyer acoustique et le diamètre du faisceau dans une marge de travail de 6 dB) dépend du degré de focalisation et du transducteur utilisé. La fréquence et la largeur de bande peuvent être influencées par l'instrumentation employée. Les profils de faisceaux théoriques sont en accord avec les profils mesurés. Diverses applications, allant de la focalisation zonale servant à déterminer l'ampleur des défauts dans les plaques épaisses jusqu'à la focalisation linéaire pour inspecter les soudures de tuyaux, font l'objet de commentaires.

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ABSTRACT

Acoustic lenses focus ultrasound to produce pencil-like beams with reduced near fields. When fitted to conventional (flat-faced) transducers, such lenses greatly improve the ability to detect and size defects. This paper describes a program developed to design acoustic lenses for use in immersion or contact inspection, using normal or angle beam mode with flat or curved targets. Lens surfaces are circular in geometry to facilitate machining. For normal beam inspection of flat plate, spherical or cylindrical lenses are used. For angle beam or curved surface inspections, a compound lens is required to correct for the extra induced aberration. Such a lens is aspherical with one radius of curvature in the plane of incidence, and a different radius of curvature in the plane perpendicular to the incident plane. The resultant beam profile (i.e., location of the acoustic focus, beam diameter, 6 dB working range) depends on the degree of focusing and the transducer used. The operating frequency and bandwidth can be affected by the instrumentation used. Theoretical and measured beam profiles are in good agreement. Various applications, from zone focusing used for defect sizing in thick plate, to line focusing for pipe weld inspection, are discussed.

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NOMENCLATURE

a	distance from the transducer face along the sound beam axis
b	depth position of the acoustic focus beneath the inspection surface
b'	depth position of the optical focus beneath the inspection surface
c	velocity of sound (subscripts indicate medium)
f	frequency
f_{ak}	acoustic focus
f_{ak}/N	focusing factor (dimensionless parameter)
f_{opt}	optical focus
h	lens depth ($=R-\sqrt{R^2-D^2/4}$)
p	sound pressure along sound beam axis of transducer
p_o	initial sound pressure at the transducer face
s	sound beam path (subscripts denote medium)
s'	equivalent time path relative to another medium
s''	equivalent distance path relative to another medium
D	transducer diameter
D_f	ultrasonic beam diameter at the focus
L_6	the 6 dB (decibel) inspection range ($=L_{6AF}-L_{6BF}$)
L_{6BF}	the location where the sound pressure drops to 50% of the maximum just before the acoustic focus
L_{6AF}	the location where the sound pressure drops to 50% of the maximum just after the acoustic focus
ΔL	the part of the inspection range distributed before the acoustic focus ($=f_{ak}-L_{6BF}$)
N	nearfield length of ultrasonic transducer ($\sim D^2/4\lambda$)

R	lens radius
R_X, R_y	lens radius in the X and Y coordinate planes
V	gain in ultrasonic signal due to focusing
X, Y, Y'	coordinate system used in lens design
α	angle rays make with an interface (subscripts denote medium)
λ	wavelength of sound
γ	angle of divergence for a sound beam $(=\sin^{-1} 1.2(D/\lambda))$

ACOUSTIC LENSES - FOCUSING IN ON DEFECTS

1. INTRODUCTION

Defect sizing is continually gaining importance as industry searches for unambiguous statements concerning quality and safety. Characterization of a defect as to type, shape, size and orientation is becoming as critical as defect detection in reducing the potential for inappropriate acceptance (component contains a rejectable flaw) or rejection (component contains no rejectable flaws). In a typical ultrasonic inspection a single unfocused transducer with a relatively large beam cross-section is used. This allows for a general evaluation of the part, but is too insensitive to detect small defects, or to accurately size those found. What is required is a focused sound field with a pencil-like profile in the region of interest. One way of achieving this is by attaching an acoustic lens to the face of a standard transducer. It is a simple and economical alternative to focusing by curved transducer surfaces, particularly when you consider that several may be required to fully cover the examination volume.

The potential applications of acoustic lenses are numerous, being suitable for immersion or contact inspection, using normal or angle beam mode with flat or curved targets. The definition of a specific working range allows for confident coverage of thick components. Correction for spherical aberration induced by curved interfaces gives a uniform beam with circular cross-section when inspecting cylindrical components. This paper deals briefly with the theoretical basis for acoustic lens design, then describes some of the practical applications. This includes fabrication of typical lenses and discussion of some practical limitations revealed.

2. THEORETICAL CONSIDERATIONS

2.1 Geometric Optics and Diffraction

In optics, the focal point (or focus) is defined as the point on the lens axis where all rays from a plane wave intersect as a result of refraction at the lens surface. If the wave intersects other surfaces, then Snell's Law applies again to give the angles of reflection or refraction. Assuming all rays to have equal travel times, a computer routine can be used to trace rays backwards from the geometric focus through the various interfaces (flat or curved, solid or fluid materials). This then defines the lens shape required to make the rays parallel as they impinge perpendicularly on the transducer face.

However, when light (or sound) passes by an edge or through an aperature, it is bent or diffracted in directions not explained by ray tracing. Diffraction is particularly important in ultrasonics due to the relatively large wavelengths involved (as compared to light). Another consideration is that the amount of light reflected or transmitted at an interface depends only on the refractive index and the angles involved. In ultrasonics, however, the governing factor is the difference in the acoustic impedances (the product of density and sound velocity).

For lenses designed using only geometric optics, discrepancies of 20 to 30% were found between predicted and measured focal lengths. The reason for this is simply that the acoustic and optical focus are not the same point, and they come into close proximity only under conditions of high focusing.

2.2 Sound Pressure Distribution

For a focused transducer, using a spherical plano-concave lens, the sound pressure (p) along the beam axis is given by[1]:

$$p = p_o \left| \frac{2}{1 - \frac{a}{R}\left(1 - \frac{c_2}{c_1}\right)} \right| \left| \sin\left[\frac{\pi}{\lambda}\left(\sqrt{(a-h)^2 + \frac{D^2}{4}} - \left(a - h\frac{c_2}{c_1}\right)\right)\right] \right| \quad (1)$$

where $h = R - \sqrt{R^2 - D^2/4}$

The calculated sound pressure is for a piezoelectric disk of diameter D, continuously vibrating in the thickness mode producing waves of length λ, at distance a, along the axis. Sound travels through the lens (sound velocity c_1) before reaching the first medium (sound velocity c_2). The initial pressure p_o just in front of the transducer face is usually set to 1.0 for plotting the function as shown in Figure 1.

In Equation 1, the first term describes the envelope of the pressure distribution, based on geometric optics. The second term describes the oscillating pressure distribution due to differences in path length between points on the outside and at the centre of the probe. These differences result in interference at some distance, a, along the axis.

Using analogous arguments, a similar equation was developed for spherical plano-convex lenses:

$$p = p_o \left| \frac{2}{1 - \frac{a}{R}\left(\frac{c_2}{c_1} - 1\right)} \right| \left| \sin\left[\frac{\pi}{\lambda}\left(\sqrt{a + \frac{D^2}{4}} - a + h\left(1 - \frac{c_2}{c_1}\right)\right)\right] \right| \quad (2)$$

Both Equations 1 and 2, however, are limited to normal beam inspection of flat surfaces using spherical or cylindrical lenses only.

2.3 Optic/Acoustic Relationships

The problem lies in finding a relationship between the optical and acoustic foci (f_{opt} vs. f_{ak} respectively). This can be done by using a slightly altered version of Equation 1 obtained by neglecting the higher order terms in the binomial expansion of the argument of sin, and using a definition of f_{opt} based on lens geometry. The resulting equation is:

$$p \sim p_o \left| \frac{2}{1 - \frac{a}{f_{opt}}} \right| \left| \sin \left[\frac{\pi}{\lambda} \cdot \frac{D^2}{8a} \left(1 - \frac{a}{f_{opt}}\right) \right] \right| \qquad (3)$$

Differentiating Equation 3 and equating to zero (to determine the position of the acoustic focus, maximum sound pressure) yields:

$$\frac{f_{ak}/N}{f_{opt}/N} \cdot \frac{2}{1 - \frac{f_{ak}/N}{f_{opt}/N}} \cdot \frac{f_{opt}}{N\pi} = \cot \left[\frac{\pi}{2} \; \frac{1}{f_{opt}/N} \left(\frac{f_{opt}/N}{f_{ak}/N} - 1 \right) \right] \quad (4)$$

The ratio f_{ak}/N (acoustic focus to near field length) is termed the degree of focusing or focusing factor ($0 \leq f_{ak}/N \leq 1$). This result was obtained by Wustenberg[2] starting from a different sound pressure distribution equation. Figure 2 plots the relation and illustrates the error introduced using f_{opt} in place of f_{ak}. For f_{ak}/N equal to 0.2, the error is only 5%, but, for a value of 0.5 the error has increased to 25%.

2.4 Lens Design Parameters

Numerical evaluation of Equation 1, 2 or 3 gives the variation in sound pressure along the axis, with the maximum pressure occuring by definition at the acoustic focus, f_{ak}. This maximum is larger than that in a non-focused field by a factor V (termed gain). Gain V indicates the increase in sensitivity (neglecting reflection losses) and the improvement in the signal to noise ratio at f_{ak}. The 6 dB inspection range (L_6) can be calculated from the locations where the sound pressure drops to 50% of the maximum just before the acoustic focus (L_{6BF}) and just after (L_{6AF}); specifically $L_6 = L_{6AF} - L_{6BF}$. The inspection range L_6 is not symmetrically distributed about f_{ak}, and the part of L_6 before the focus is given as $\Delta L = f_{ak} - L_{6BF}$.

Each of the above parameters can be plotted as a function of the focusing factor as shown in Figures 2 and 3. These curves can be described analytically by the following equations[2]:

$$\frac{f_{opt}}{N} = \frac{1}{1 - \frac{f_{ak}}{N}} \left(\frac{f_{ak}}{N} - 0.635 \left(\frac{f_{ak}}{N} \right)^2 + 0.2128 \left(\frac{f_{ak}}{N} \right)^3 \right) \quad (5)$$

(Deviation < ± 9%)

$$V = \frac{1.9}{\frac{f_{ak}}{N}} - 0.9 \quad (6)$$

(Deviation < ± 5%)

$$\frac{L_6}{N} = \left(\frac{f_{ak}}{N} \right)^2 \left(\frac{2}{1 + \frac{1}{2} \frac{f_{ak}}{N}} \right) \quad (7)$$

(Deviation < ± 3%)

$$\frac{\Delta L}{L_6} \sim \frac{1}{4} \left[1 + \left(1 - \frac{f_{ak}}{N}\right)^2 \right] \quad (8)$$

(Deviation < ± 5%)

Ultrasonic theory also shows that the beam diameter within the acoustic focal range can be given approximately by:

$$D_f \sim \frac{D}{4} \cdot \frac{f_{ak}}{N} \quad (9)$$

3. DESIGNING AN ULTRASONIC LENS SYSTEM

3.1 General

Having established inspection requirements, the following are defined or selected:

- the depth position of the acoustic focus (b),
- the inspection angle (α_1),
- the transducer diameter (D) and frequency (f),
- the length of the wedge (solid or fluid) between lens and target.

The design is then carried out in two steps:

1) Determine the position of the optical focus based on the preset nearfield length and position of the acoustic focus.

2) Define the lens curvature to produce the desired acoustic focus (assuming equal travel times for each ray from the optical focus to the transducer face, and obeying Snell's Laws at each interface).

3.2 Position of Optical Focus

The geometry used in the lens design is illustrated in Figure 4. The distance from the transducer face to the acoustic focus includes paths through the lens (s_3), the wedge section (s_2), and the target material itself. In order to add these distances together they must first be converted to equivalent paths. This is done by multiplying by the velocity ratio:

$$s''_2 = s_2 \frac{c_2}{c_1} \tag{10}$$

where s''_2 is the "equivalent distance path" in material 1 of distance s_2 in material 2. This is to be distinguished from the "equivalent time path" which is:

$$s'_2 = s_2 \frac{c_1}{c_2} \tag{11}$$

where an ultrasonic ray would travel path s'_2 in material 1 in the same time it would travel path s_2 in material 2.

In determining the position of the acoustic focus, the equivalent path of the wedge section must be chosen so as not to produce echos from the wedge/target interface which would mask defects within the desired inspection range. This is easily checked if the equivalent time path of the wedge section relative to the target material is used. This problem is not as important with angle beam inspections; however, consideration must still be given to design of the wedge section to ensure adequate dissipation of sound energy reflecting off the wedge/target interface. Because the lens thickness is usually quite small (less than ∿ 5 mm) reverberations within the lens usually do not cause problems.

Combining all paths together and remembering the effects of damping and attenuation, the distance to the acoustic focus (relative to the target material) is given by:

$$f_{ak} = \frac{b}{\cos\alpha_1} + s'_2 \left(\frac{c_2}{c_1}\right)^2 + s'_3 \left(\frac{c_3}{c_1}\right)^2 \qquad (12)$$

or

$$f_{ak} = \frac{b}{\cos\alpha_1} + s_2 \left(\frac{c_2}{c_1}\right) + s_3 \left(\frac{c_3}{c_1}\right) \qquad (13)$$

Having calculated f_{ak}, then the position of the optical focus can be determined from Figure 2 or Equation 4 or 5. The diameter of the focal range, its position and length can be calculated from Equations 7, 8 and 9 or from Figure 3. If the values for D_f and L_6 are not suited to the given requirements, then another transducer (diameter and/or frequency) must be used. Alternatively, some limited variation in D_f and L_6 can be obtained by changing the length of the wedge section.

3.3 Lens Curvature Definition

Based on the assumption that all rays require the same time to travel from the optical focus to the transducer face, points on the lens surface can be defined. Regression analysis can then be applied to the points to determine the best-fit circular arc (circular to facilitate machining) or whether the surface can indeed be approximated by a circle or not. This must be done both for the plane of incidence and the one perpendicular to it.

The use of the computer routine at this stage to define the lens surface requires input of the acoustic velocities involved, the inspection angle, the number of rays to be traced and the angle between them. The routine can accommodate flat as well as curved target surfaces.

The two mutually perpendicular circles give only an approximation to the surface required to focus all rays at f_{ak}. In fact, circular or spherical lenses cannot focus rays to a single point, giving instead a fuzzy or hazy focus (known as spherical aberration); however,the spherical approximation is allowable provided $R/D>1$.[2]

4. FEASIBILITY STUDY

4.1 Manufacturing Process

Numerous lenses were designed and fabricated for use in normal and shear wave, immersion and contact inspections. Acryllic and polystyrene were used for the lenses and wedges. Initial machining of compound lenses was done using a "flywheel cutter". The profile of a knife edge cutter provided one radius, and the radial location of the cutter on the rotating flywheel gave the other radius on the lens. This technique had several disadvantages including the necessity of a new cutter for each new radius, and excessive tool tip forces. The preferred technique uses a single-point tool mounted on a boring head attachment for a milling machine. The piece to be machined is supported off a turntable. While the tool in the boring head cuts one radius on the lens, simultaneously the turntable is rotated to define the second radius perpendicular to the first. Results indicate that this is an easily reproducible procedure with acceptable accuracy limitations.

4.2 Experiment Versus Theory

Three compound lenses and four spherical lenses were designed for use with a 25.4 mm, 5.0 MHz transducer for shear wave contact inspection of steel plate. Focusing factors of 0.3 to 0.75 were chosen to cover the full thickness of the plate. Beam profiles were made for two of the lens/wedge assemblies using a test block containing a series of side drilled holes (see Figure 5), and an ultrasonic instrument which closely reproduced the theoretical nearfield length of the chosen transducer. All lens/wedge assemblies were profiled using a second instrument in immersion and contact mode. In all cases, results were consistent with previous work[3]. Beam profile data indicated that the beam cross-sections were essentially circular, but that measured beam diameters were approximately 30 percent larger than design diameters. Detailed results for the two assemblies are given in Table 1 with corresponding beam profiles in Figures 6 and 7.

5. PRACTICAL CONSIDERATIONS

5.1 Immersion Versus Contact

For comparison with results obtained using contact techniques all lens/wedge assemblies were also profiled with the same instrument using an immersion tank with a spherically-ended 3.2 mm diameter rod as the target. This is a much simpler means of obtaining a beam profile as only one target is used, and it is easy to change the path length between transducer and target in as small steps as desired. Once converted to equivalent pathlengths in steel, the measured focal lengths using immersion agreed with results using contact within ±2.5 percent as shown in Table II. This difference is of the same magnitude found in doing consecutive profiles on the same assembly. The relation between focusing longitudinal waves in water to focusing shear waves in steel removes the necessity for elaborate test blocks, fancy equipment and lengthy contact inspection procedures to verify a lens design.

5.2 Instrumentation Effects

The focal length of an ultrasonic transducer depends on the operating frequency of the transducer. This in turn is affected by the instrumentation used for excitation. To illustrate the relevance of this to acoustic lens design, the two assemblies detailed in Table I were profiled again using other ultrasonic instruments. The measured focal lengths (see Table III) varied by as much as 30 to 40 percent. The largest variation occured between supposedly identical instruments from the same manufacturer.

Table III basically illustrates the effect instrumentation can have on beam characteristics for a given transducer. The nearfield length (N) of an unfocused transducer is given approximately by:

$$N \sim \frac{D^2}{4\lambda} \qquad (\text{Note: } \lambda = \frac{c}{f}) \qquad (14)$$

and the angle of beam divergence (γ) is given by:

$$\sin\gamma = 1.2\left(\frac{\lambda}{D}\right) \qquad (15)$$

However, the actual nearfield length and beam diameter (as determined by the angle of divergence) depend on the frequency response of the particular transducer to the particular instrument being used, and are also dependent on the selection of instrument variables such as pulse energy and damping. The nearfield length is used throughout the design procedure for acoustic lenses. If there is a 10 percent error in the value of the nearfield, then it may result in a 10 percent error in beam diameter, and a significantly larger error in focal length for the focused probe, depending on the relative path lengths in lens/wedge and target materials. For some commercially available transducers, this nearfield length error is closer to 50 percent. Accordingly, to save time and effort, the nearfield of an unfocused transducer should be determined prior to doing the lens design. The results described here further suggest that for critical applications beam profiles should be done with the actual transducer/instrument combination to be used for that application.

6. APPLICATIONS

Acoustic lenses have potential application anywhere focused beams are required. One such obvious application is he sizing of defects. Apart from the stronger signal obtained from a higher intensity beam, it is possible to better characterize the defect because of the narrow beam. In order to do this, however, it is necessary to find the defect in the first place. If it is a large, poorly oriented plane defect then this can be difficult, if not impossible, to do. By making use of the "border effect", the probability of missing such a defect is minimized when using focused beams[4]. This has particular applicability to crack sizing, and consequently is important to in-service inspection where crack propagation is of prime concern.

For thick-walled components, the inadequacy of existing standards allows for wide variability in interpretation of ultrasonic readings. Recognitiion that this can no longer be tolerated has led to international attempts to define limitations of present standard inspection procedures, and to assess proposed alternatives. The enhanced ability to detect and size small but potentially dangerous flaws makes focused probes one of these alternatives. Because the working range of a focused probe is generally small, several units may be required to adequately inspect a thick component. The extent of the working range depends on the focusing factor (as shown in Equations 7 and 8). This means that for a 250 mm thick plane and using a 70° inspection angle, seven transducer/lens combinations might be required as shown in Table IV. If the beam diameter requirements were relaxed at the greater depths, then the number of required focal zones could be reduced to five. Using five different inspection angles the number of focused probes grows rapidly, with acoustic lenses providing an economical and practical solution to the problem.

Recently, acoustic lenses have been used in ultrasonic B-scan imaging. Contrary to the traditional B-scan where the transducer is moved along the test piece at a fixed inspection angle, the transducer is rotated through an arc so that the inspection angle is varied while maintaining a common entry point (termed a Sector B-scan). Initial tests showed that the depth of focus beneath the target surface varied greatly due to mode conversion from longitudinal to shear as the transducer rotated past the first critical angle. Because the Sector B-scan was intended for use in weld inspections, a cylindrical lens was designed to produce a line focus at the required depth. To address the problem introduced by mode conversion, the cylindrical surface contained two radii: one radius to focus the longitudinal waves at the desired shallow penetration, and a second larger radius to give deeper penetration for the shear waves, but maintaining the focus at approximately the same depth beneath the surface as for the longitudinal waves.

Acoustic lens design has just as much to offer in the traditional inspection of pipeline welds. The use of focused beams makes it possible to maximize defect detectability throughout the weld configuration. Besides providing the desired focusing effects, the lens/wedge combination also determines the angle at which the sound beam enters the inspection piece. Working backwards then, given a particular weld configuration, it is possible to determine the necessary lens/transducer combinations to provide the required inspection angles and focal zones. This is particularly the case if past experience has identified a region of concern (e.g., lack of fusion in the root area). It is possible that several lens/transducer combinations may be required for different inspection angles or to look at different areas. These could be mounted in an assembly so that all the information could be obtained in one scan of the pipe.

7. CONCLUSION

Acoustic lenses provide a simple means to focus in on defects. Results indicate that required focal lengths and beam diameters can be readily produced following a systematic design procedure. There are however some practical limitations. Resultant beam diameters tend to be slightly larger than design. This can be readily corrected for by using a design value approximately 30 percent smaller than required. Also, instrumentation can have a significant effect on the focused beam characteristics. For critical applications resultant beams should be profiled using the actual transducer/lens/instrument combination to be used for that application. Irrespective of these limitations, acoustic lenses provide an economical way to obtain a focused beam for a wide variety of uses and applications.

8. REFERENCES

1. Schlengermann, U., "Schallfeldausbildung bei ebenen Ultraschallquellen mit fokussierenden Linsen", Ac‥stica, Volume 30, Issue 6, 1974, pp 291-300.

2. Wustenberg, H., Kutzner, J., Mohrle, W., "Fokussierende Prufkopfe zur Verbesserung der Fehlergroßenabschatzung bei der Ultraschallprufung von dickwandigen Reaktorkomponenten", Materialpruf, 18, number 5, 1976 May.

3. Larsen, R.E., "Zone-Focused Search Units for Bore Ultrasonic Examination Series", Proceedings of the Twelth Symposium on Nondestructive Evaluation, San Antonio Texas, 1979 April 24-26.

4. De Vadder, D., Azou, P., Saglio, R., "Determination of Orientation and Size of Badly Oriented Defects by Means of Focused Probes", Proceedings of the First International Symposium on Ultrasonic Materials Characterization held at NBS, Gathersburg, Maryland, USA, 1978, June 7-9.

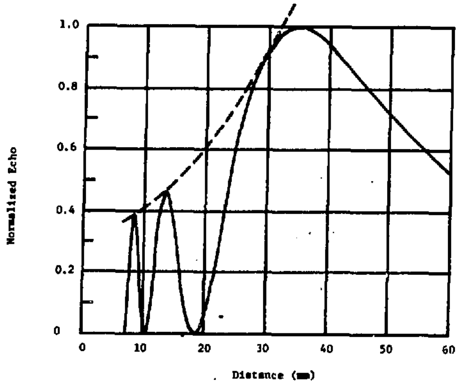


FIGURE 1: Plot of Schlengermann's equation for the sound pressure distribution along the axis in water.

D=10 mm, f=3.0 MHz, R=33 mm, f_{opt}=70 mm, f_{ak}=35 mm, f_{ak}/N=0.683

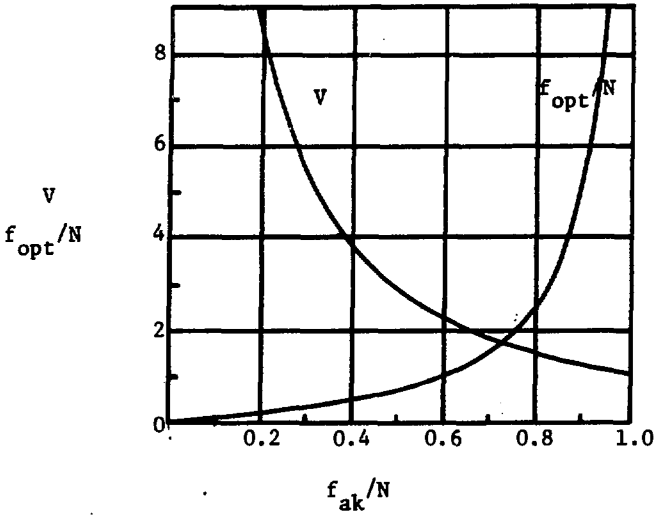


FIGURE 2: Plot of focusing factor versus gain (V vs. f_{ak}/N) and normalized optical focus (f_{opt}/N vs. f_{ak}/N).

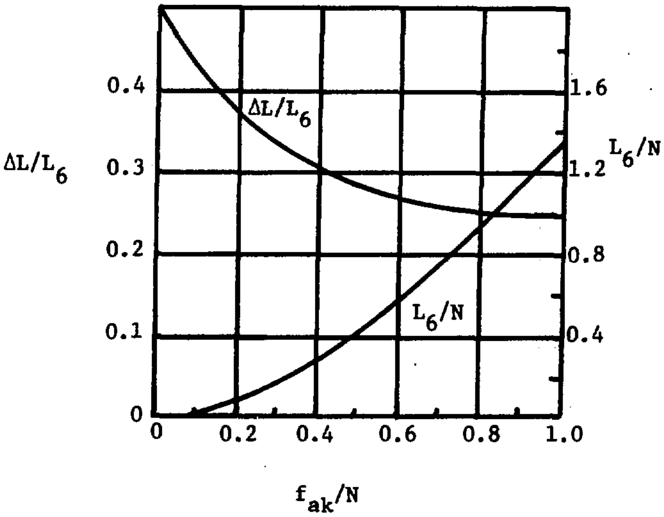


FIGURE 3: Plot of focusing factor versus normalized inspection range (L_6/N vs. f_{ak}/N), and portion of the inspection range before the focus ($\Delta L/L_6$ vs. f_{ak}/N).

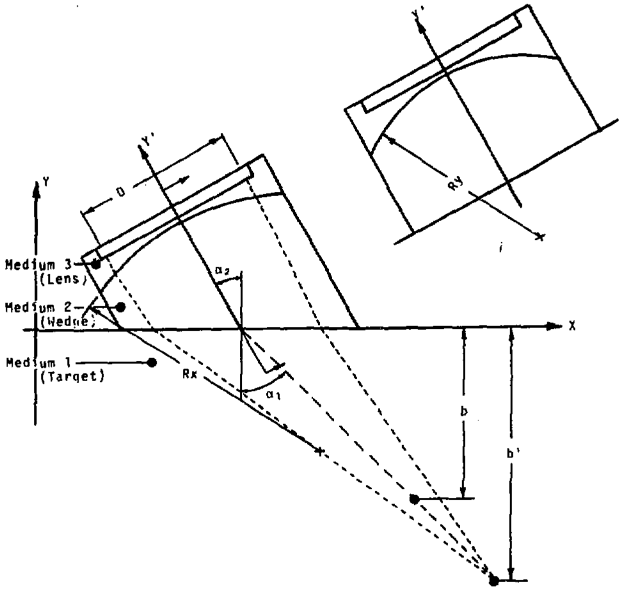
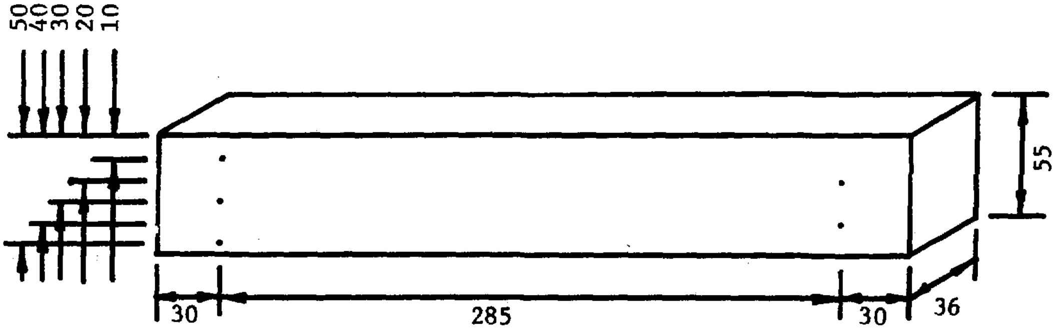
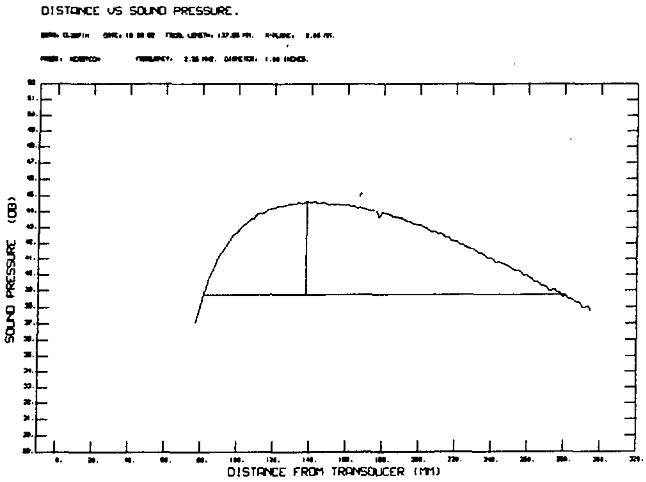


FIGURE 4: Geometry used in acoustic lens design.

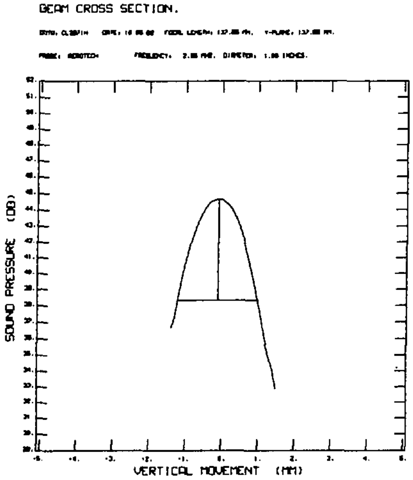


Dimensions in mm

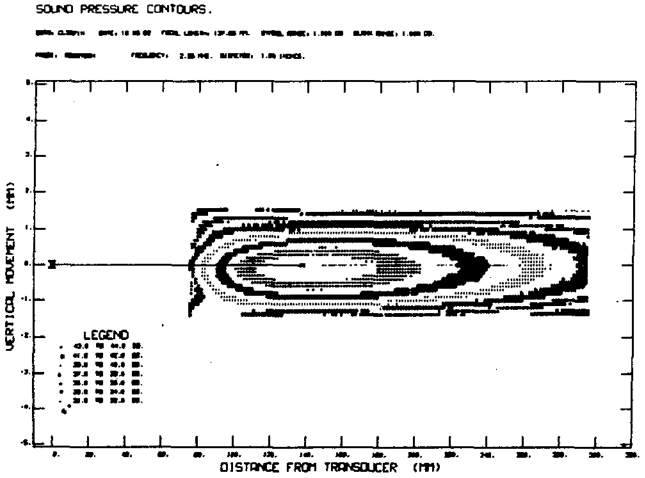
FIGURE 5: Test block used in beam profiling.



a) Distance versus sound pressure.

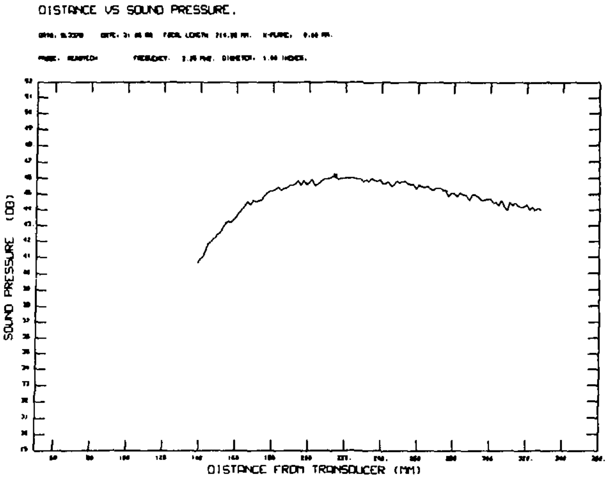


b) Beam cross-section.

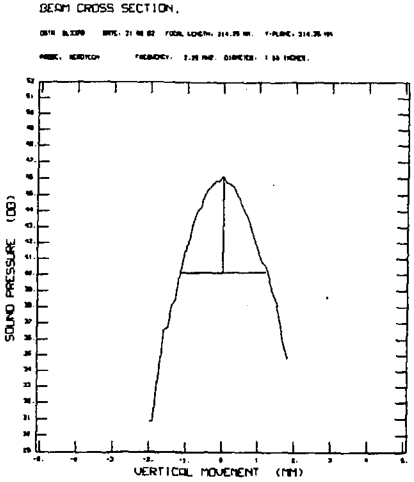


c) Sound pressure contours.

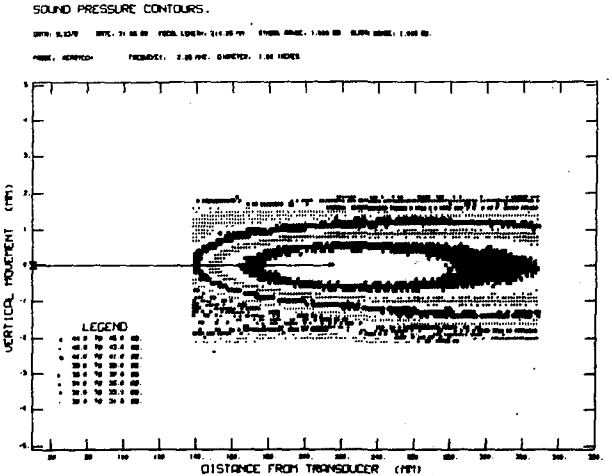
FIGURE 6: Beam profile data.
D=25.4 mm, f=2.25 MHz, R_X=25.3 mm, R_Y=36.9 mm, f_{ak}/N=0.535



a) Distance versus sound pressure.



b) Beam cross-section.



c) Sound pressure contours.

FIGURE 7: Beam profile data.
$D=25.4$ mm, $f=2.25$ MHz, $R_X=R_Y=87.9$ mm, $f_{ak}/N=0.7575$

TABLE I: BEAM PROFILE DATA

	SYMBOL	ASSEMBLY C2 DESIGN	ASSEMBLY C2 MEASURED	ASSEMBLY S3 DESIGN	ASSEMBLY S3 MEASURED
Focusing Factor	f_{ak}/N	0.5350		0.7575	
Depth Position of f_{ak}	b (mm)	29.7	28.1	47.4	45.4
Beam Diameter	D_f(mm)	3.4	Horiz. 5.0 Vert. 4.1	4.81	Horiz. 6.15 Vert. 5.53
6 dB Inspection Range	L_6(mm)	50.74	55	95.52	91

Probe - Diameter	D (mm)	25.4		c_1(km/s)	3.23
- Frequency	f (MHz)	2.25	Sound Velocities	c_2(km/s)	2.23
Wavelength in Target	λ (mm)	1.44		c_3(km/s)	2.74
Inspection Angle	α (°)	45			

TABLE II: IMMERSION VERSUS CONTACT FOR DETERMINING BEAM PROFILES

LENS/ WEDGE ASSEMBLY	IMMERSION TEST DATA: WATER PATH TO FOCAL POINT (mm)	EQUIVALENT PATH IN STEEL (mm)	TIME IN PLASTIC (μs)	TIME TO FOCAL POINT (μs)	CONTACT TEST DATA: TIME TO FOCAL POINT (μs)	% DIFFERENCE
C2	120.4	55.76*	12.2	58.9**	60	-1.8+
C3	179.7	83.23	11.7	74.9	75	-0.1
C4	122.2	56.60	15.2	65.4	64.0	2.2
S2	137.9	63.87	11.7	62.9	62.5	0.7
S3	190.3	88.14	11.6	77.8	76	2.3
S4	103.8	48.08	18.5	66.8	66	1.2
S5	55.7	25.8	18.4	52.8	54	-2.3

*$120.4 \times \frac{1.496}{3.23} = 55.76$

C2–C4: Compound Lenses
S2–S5: Spherical Lenses

** $\left(\frac{55.76}{3.23} + 12.2\right) \times 2 = 58.9$

+ % Difference = $\frac{58.9-60}{60} \times 100 = -1.8\%$

TABLE III: FOCAL LENGTH VARIATION WITH INSTRUMENTATION

	PATH IN STEEL (mm)				
		ULTRASONIC INSTRUMENTS USED			
LENS WEDGE ASSEMBLY	DESIGN	USIP 11	USIP 11	KB6000	M90
C2	42	40	58	40	50
S3	67	64	85	--	--

TABLE IV: ZONE FOCUSING AS APPLIED TO A 250 MM THICK STEEL PLATE USING A 70° INSPECTION ANGLE

ZONE	TRANSDUCER		f_{ak} (mm)	f_{ak}/N	WORKING RANGE (mm)	D_f (mm)
	DIA. (mm)	FREQ. (MHz)				
1	76.2	5.0	600	0.27	500-700+	5.1
2	76.2	2.25	400	0.40	300-575	5.0
3	76.2	2.25	250	0.25	200-300	4.8
4	50.8	2.25	150	0.33	100-200	4.2
5	38.1	2.25	75	0.30	60-100	2.8
6	38.1	2.25	50	0.20	40-60	1.9
7	25.4	2.25	30	0.27	25-40	1.7

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