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Focusing Ultrasound with Zone Lenses

by

Alireza Shirazi Hosseini D., B.Sc.

**A thesis submitted to the Faculty of Graduate Studies and Research in partial
fulfilment of the requirements for the degree of Master of Science**

Department of Physics

Carleton University

Ottawa, Ontario

April 1991

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submitted by

Alireza Shirazi Hosseini D., B.Sc.

**in partial fulfilment of the requirements for
the degree of Master of Science**

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FOCUSING ULTRASOUND WITH ZONE LENSES

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April 1991

ABSTRACT

The purpose of this study was to develop a method of designing an acoustic zone lens from plexiglass to produce a focus from the field of a plane circular ultrasonic transducer at a specific frequency.

Theoretical aspects of simple and zone lenses are reviewed. To that end, the passage of ultrasound across interfaces and the focusing of ultrasound with simple and zone lenses are discussed in terms of beam patterns, *FWHM*, size of focal spot and step size of zone lens. The geometry of a simple plano-concave lens in terms of focal point or region is discussed and a method of calculation of focal point or region is described. The step size of zones, which is the essential feature, is discussed and calculated.

The transducer, a 32.1 mm effective diameter PZT disk, has 1.05 MHz centre frequency. Simple and zone lenses are plano-concave, each of 60 mm diameter, focal length of about 105 mm, and radius of curvature of 46.75 mm. Step sizes of the zone lens are about 3.22 mm, having three zones of equal area.

A precision apparatus to control and align a hydrophone with respect to the transducer acoustic axis is described. Experimental data (acoustic pressure fields of a series of simple and zoned lenses) were acquired, using a needle hydrophone of 0.6 mm diameter. The acquisition system and data processing were carried out by a micro-computer.

The *FWHM*, size of focal spot and depths of focus of simple and zone lenses are compared. The experimental results demonstrate agreement within $\pm 4\%$ between theoretical expectation and the measured value.

The *FWHM* values and size of focal spots are about equal and agree with theoretical predictions to within $\pm 4\%$. The depth of focus of the zone lens agrees with simple theory and shows a decrease of 21% compared to the simple lens. The appearance of the side lobes for the zone lens resembles the *Airy* shape more than that of the simple lens.

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CHAPTER 1

Introduction

Almost from the beginning of the development of ultrasonic technology there has been considerable interest in use of ultrasound radiation for medical purposes. The radiation was used, for imaging and therapy, in modes somewhat analogous to those utilizing ionizing radiation. Some good general surveys and historical reviews of this field are given in references [1,2,3,4,5,6].

Within the framework of ultrasound technique, focused fields are required in many applications for increasing the intensity and the resolving power. Such fields are utilized in medicine, non-destructive testing of materials, cleaning and welding with

ultrasound, under-water imaging and acoustic microscopy. Ultrasonic devices which are in use, for medical applications range from simple physiotherapy therapy units to sophisticated scanners, to give diagnostic information not possible with any other conventional techniques. All these machines use transducers of plane faced or focused type. In case of a plane ultrasonic transducer, ultrasonic energy is mainly confined in the near field within a cylinder of diameter equal to that of the transducer, lying symmetrically along its perpendicular axis. In the far-field the energy spreads in a spherical fashion. The lateral resolution of a transducer, in the near field, is a fraction of the minimum transducer width, which can be reduced by reducing the transducer diameter. To achieve the best resolution, high frequencies may be used. However, high frequency systems pose problems of poor far-field resolution, more attenuation at high frequencies, and decrease of ultrasonic power output. These problems are partly overcome when one uses focused transducers as the focusing provides resolution even upto one wavelength. The focusing concentrates the total energy emanating from a relatively large area to the relatively small focused point. Ultrasound beam focusing is obtained mainly with the help of an *acoustic lens*, a mirror, a shaped crystal or by electronic means [7].

Acoustic lenses have a long history [8]. They can be traced back to as early as 1852 when Sondhaus constructed one by filling a thin film of collodium with carbon dioxide. Given that the speed of sound in carbon dioxide is less than in air, a convex lens could focus sound as an optical lens focuses light. Lord Rayleigh also described an acoustic lens in 1879 [9]. Since then many researchers [8] have

dealt with the theory and applications of acoustic lens. Over the past several decades, various types of acoustic lenses have been investigated [10,11]. Acoustic lenses have been widely used in the areas of high resolution sonar [12], nondestructive testing for materials inspection systems [13], medical diagnostic imaging [14], under water imaging [15] and acoustic microscopy [16].

Plastic acoustic lenses have been used in high-intensity focused ultrasound by different investigators, e.g. for neurological studies (Robinson et al,1969),[27] and in the liver for the treatment of discrete liver tumours (ter Haar et al,1989) [28].

Lenses may, in principle, be made of any material that can be given the required shape and has the required difference between its acoustic velocity and that of the surrounding medium, and has a low absorption. From the point of view of manufacture and impedance matching, certain conventional plastics are preferred, that is, plastic appears to be the best material readily available for minimizing reflection at the surface. However, when intensities of the order of a few watts per sq. cm are transmitted through the lens it is found that heating becomes so severe that moderate to severe damage can occur within a few seconds [26]. This heating is certainly volume heating [17].

Metal lenses, aluminum, stainless steel, brass, or possibly other materials can easily withstand the heating. However, the acoustic mis-match between the lenses and the water medium is so severe that the overall system efficiency is much too low to be practical.

For the present, it seems best to stay with plastic lenses. In the past, various

plastic materials have been considered, but finally from considerations of ultrasound absorption, durability, availability and machining properties, conventional acrylic, that is lucite, is the best practical choice.

As stated above, a severe limitation of plastic lenses is their eventual, and sometimes fairly prompt, destruction by the ultrasound field. This may take two forms.

Lenses designed to produce a high intensity focused spot are typically 2 cm thick at the rim. Consequently, a significant amount of heat is deposited in the body of the lens, and with poor thermal conductivity of acrylic, even though the surrounding medium is water, there is a marked temperature rise internally. This can result in sufficient expansion to crack the lens, typically a rather neat circular crack about a centimetre from the rim [17,26]. Alternatively, it can result in near surface melting, production of gas, and hence bubbling and blistering. There is a second form of damage which takes the form of a small blister at the precise centre of the lens. This appears at a quite low power and the origin of this effect is not known [17].

As a method of avoiding the bulk heating, it is proposed to use "zoned lenses". These consist of a set of lens surfaces, radially separated, all focused to the same axial point. The zones will be axially placed so that the outer zones will have an acoustical path length to the focus that differs by an integral number of wave lengths from the inner zone. Thus, at the design frequency for continuous waves, all the zones combine coherently to produce a normal looking focus, but the overall thickness of the lens will be reduced so the heating is less, and the conductivity is enhanced [17]. The

lens configuration is shown schematically in Figure 1.1.

The purpose of this study is to design a zone lens as outlined above and compare its performance with simple plano-concave lens with respect to quality of the focal spot. It should also be noted that our concern was a therapeutic use of zone lens and not imaging. Therefore, the ultrasonic mode of experiments was continuous wave (CW) rather than pulse mode.

A discussion of the passage of ultrasound across an interface and ultrasonic beam pattern is given in chapter two. Chapter three discusses focused ultrasound, its beam pattern and zone lenses. Chapter four and five give experimental procedures and results.

Simple Lenses

6

Figure 1.1 Typical configuration of lenses, (a) Simple lenses, (b) Zone lens.

CHAPTER 2

Propagation of Ultrasound

Ultrasound is conventionally defined as acoustic waves with frequencies above about 20 KHz. As the frequency is increased, the wavelength of these waves get progressively smaller, and this small size accounts for some of the unique resolution capabilities of ultrasound. Medical instrumentation typically uses only the portion of the ultrasound spectrum from 1 MHz to 10 MHz due to the combined needs of good resolution (small wavelength) and good penetrating ability (not too high a frequency). The waves are generated by small acoustic transducers that are electrically driven.

The essence of any sound wave is that particles of a transfer medium are set into motion (e.g. periodic motion) by a sound source, such as the voice or a transducer. The various forces on the particles causing them to respond in a harmonic oscillation, which is propagated through the medium.

The theoretical treatment of sound propagation has been given by numerous authors. The classical work is that of Rayleigh [9]. The application to ultrasound, and particularly ultrasound for medical purposes has likewise been the subject of numerous studies [2,3]. The summary given here follows closely that of Christensen [18].

2.1 The Wave Equation

To develop the longitudinal acoustic wave equation, consider an infinitesimal volume element of the supporting material as shown in Figure (2.1). By applying Newton's laws and conservation of mass [2,3,18] one can obtain, for example, the following wave equation :

$$\frac{\partial^2 p}{\partial x^2} - \rho_0 K \frac{\partial^2 p}{\partial t^2} = 0 \quad (2.1)$$

This is the one-dimensional wave equation for the propagation of plane waves in the z direction. In a fluid this must be a longitudinal pressure wave where p is the pressure, ρ_0 is the average material density (a constant), t is the time and K is the *adiabatic compressibility* constant for the material. Over a limited range of pressure K is given by :

Figure 2.1 Pressure and velocities in an infinitesimal volume of material,
(after Christensen [18]).

$$\rho_1 / \rho_o = Kp \quad (2.2)$$

where the ρ_1 is the density at pressure p . A similar wave equation may be obtained for the particle velocity u

$$\frac{1}{K} \frac{\partial^2 u}{\partial x^2} - \rho_o \frac{\partial^2 u}{\partial t^2} = 0 \quad (2.1a)$$

For a harmonic wave travelling in the $+z$ direction, equation (2.1) has a solution

$$p = p_+ \cos (\omega t - kz) \quad (2.4)$$

where p_+ is an amplitude constant, ω is the angular frequency of the wave in radians per second, and k is the so-called propagation constant. A similar solution is obtained for u . Substitution of equation (2.4) into the wave equation (2.1) shows that it is indeed a valid solution provided that the following relationship always holds :

$$k^2 = \rho_o K \omega^2 \quad (2.5)$$

In other words, the material will support a pressure wave of the form of equation (2.4) for which the frequency ω and propagation constant k are related by equation (2.5).

Equation (2.5) is known as the *dispersion equation*, or Brillouin equation, and since the constants ρ_o and K appear, it is specific to the medium supporting the wave.

A more general solution, with arbitrary phase, is

$$p = p_+ \cos (\omega t - kz + \phi) \quad (2.6)$$

where ϕ is an arbitrary phase angle. Again the dispersion equation must apply for this wave to be a valid solution. For plane compressional acoustic waves, equation (2.5) gives

$$\omega^2 = \left(\frac{1}{\rho_o K} \right) k^2$$

Or since $c = \omega / k$, the phase velocity for these waves is

$$c = \frac{\omega}{k} = \frac{1}{\sqrt{\rho_o K}} \quad (2.7)$$

which is a function of the average density ρ_o and compressibility K of the material in which the waves are propagating.

2.2 Impedance of a Medium

Since the same pair of equations leads to solutions for both p , equation (2.1) and u , equation (2.1a) it is natural to expect that some relationship always exists in the medium between the quantities p and u [18].

The ratio of particle pressure p and particle velocity u is a constant for a given medium. This leads to the definition of the *specific or characteristic acoustic impedance*:

$$Z = p / u \quad (2.8)$$

By using wave equations [18] one may obtain the following :

$$Z = \omega \rho_o / k = \rho_o c \quad (2.9)$$

Since the value of $\rho_o c$ is characteristic of a particular material, the quantity $\rho_o c$ is sometimes called its characteristic impedance.

Another form for the impedance can be obtained by substituting equation (2.7), which relates phase velocity to material properties, into equation (2.9) :

$$Z = \rho_o \left(\frac{1}{\sqrt{\rho_o K}} \right) = \sqrt{\frac{\rho_o}{K}} \quad (2.10)$$

Equation (2.9) and (2.10) both show that the impedance of a medium depends upon its mechanical properties, and it will vary from material to material.

With impedance now defined, expressions for the particle velocity u can be obtained immediately, corresponding to any solution for the pressure p . For example, if the pressure wave is

$$p = p_+ \cos(\omega t - kz) \quad (2.4)$$

then the particle velocity wave accompanying this pressure is

$$u = p_+ / Z \cos(\omega t - kz) = u_+ \cos(\omega t - kz) \quad (2.11)$$

Note that the pressure wave and the velocity wave are always in phase for the case of lossless plane waves.

2.3 Power Density

Now that expressions have been found for both particle velocity and pressure, we can derive an expression for the power density carried by the wave. The instantaneous power flowing through a unit area perpendicular to the direction of propagation of the wave as one elemental volume of the fluid acts on a neighbouring element is defined as the wave's *power density* and is given by [18]

$$\text{Power Density} = I = pu \quad (2.12)$$

So, using equation (2.8),

$$I = p^2 / Z = Z u^2 \quad (2.13)$$

The total power of a uniform wave is given by the product of its power density I and its cross-sectional area A .

In Figure (2.2), I is plotted as a function of distance for a sinusoidal pressure wave at one instant of time. Note that I is always a positive quantity and the spacing between power peaks is one-half a pressure wavelength.

As a practical matter it is often more convenient to consider the space average of the power density. The space average of I for a sinusoidal acoustic wave $p = p_+ \cos(\omega t - kz)$ can be found by simply integrating the instantaneous power density over one wavelength, then dividing by one wavelength :

$$I_{ave} = \frac{1}{\lambda} \int_0^{\lambda} \frac{p^2}{Z} dz = \frac{k}{2\pi} \int_0^{\frac{2\pi}{k}} \frac{p^2}{Z} \cos^2(\omega t - kz) dz = \frac{p^2}{2Z} \quad (2.14)$$

Thus, the average power density (or *intensity*) for a sinusoidal wave is just one-half of its peak value. A time average of I will yield an identical result.

Figure 2.2 Variation of particle velocity u and power density I corresponding to a pressure wave of the form $p = p_0 \cos(\omega t - kz)$. I has an average value equal to one-half its peak value, (after Christensen [18]).

2.4 Reflection and Transmission

In a propagating wave, there are no sudden discontinuities in either particle velocity or particle pressure. Consequently, when a wave meets the interface between two media, both the normal velocity component and the pressure are continuous across the interface. In physical terms, this ensures that the two media remain in contact. Figure 2.3 shows the pressure and particle velocity vectors which are associated with each wave immediately adjacent to the interface between medium 1 and medium 2. Here, there is a wave incident from the left, giving rise to a transmitted wave on the right side of the boundary and a reflected (left directed) wave on the left. Since the pressure of each wave acts in all directions, and since the boundary itself does not supply any resistance, the net pressure on the left side of the boundary must equal the net pressure on the right side of the boundary. This fact gives a relationship between the three pressures, as :

$$p_t = p_i + p_r \quad (2.15)$$

It is also required that the net velocity components of the particles perpendicular to the left boundary side must be equal to the perpendicular velocity component on the right side. Otherwise the media would pull apart from each other at the boundary. Thus one may write :

$$u_t \cos \theta_t = u_i \cos \theta_i - u_r \cos \theta_r \quad (2.16)$$

The normal angles (θ_i , θ_r , θ_t) are defined in Figure 2.3.

Figure 2.3 the pressure and particle velocity vectors which are associated with each wave immediately adjacent to the interface between medium 1 and medium 2, (after Christensen [18]).

This requirement on the velocities may be related to the respective pressures through the impedance equation, equation (2.8). Therefore :

$$(p_r / Z_2) \cos \theta_r = (p_i / Z_1) \cos \theta_i - (p_t / Z_1) \cos \theta_t, \quad (2.17)$$

The simultaneous solutions to equations (2.15) and (2.17) are given by :

$$R = \frac{p_r}{p_i} = \frac{Z_2 \cos \theta_i - Z_1 \cos \theta_t}{Z_2 \cos \theta_i + Z_1 \cos \theta_t} \quad (2.18)$$

And

$$T = \frac{p_t}{p_i} = \frac{2 Z_2 \cos \theta_i}{Z_2 \cos \theta_i + Z_1 \cos \theta_t} \quad (2.19)$$

The quantities $R = (p_r / p_i)$ and $T = (p_t / p_i)$ are respectively *the pressure reflectivity* and *the pressure transmittivity* of the interface [3].

At normal incidence, $\theta_i = \theta_t = 0$, and equation (2.18) and (2.19) become :

$$R = \frac{p_r}{p_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (2.20)$$

And

$$T = \frac{p_t}{p_i} = \frac{2 Z_2}{Z_2 + Z_1} \quad (2.21)$$

Figure 2.4 shows an example of an incident acoustic wave with pressure p_i and

particle velocity u , divided into reflected and transmitted waves at the interface between two media with impedances Z_1 and Z_2 , respectively.

We often are more interested in reflected power, so the relationship between pressure and power density, equation (2.13), may be used to give the following ratio, valid for any angle of incidence :

$$\frac{I_r}{I_i} = \frac{p_r^2/Z_1}{p_i^2/Z_1} = R^2 \quad (2.22)$$

Also of interest is the amount of power density remaining in the transmitted portion of the wave after passage through the boundary. The power densities of the incident and transmitted waves are given by equation (2.13) :

$$I_i = p_i^2 / Z_1 \quad (2.23)$$

$$I_t = p_t^2 / Z_2 \quad (2.24)$$

with boundary condition $p_i = p_t + p_r$, the equations (2.23) and (2.24) give the following ratio :

$$\frac{I_t}{I_i} = \frac{[1 + (p_r/p_i)]^2 Z_1}{Z_2} = (1 + R)^2 \frac{Z_1}{Z_2} \quad (2.25)$$

The principle of the conservation of energy states that the total amount of power entering the boundary must equal the total amount of power leaving. Thus,

$$I_i A_i = I_r A_r + I_t A_t \quad (2.26)$$

where A_i , A_t , and A_r are the cross-sectional areas of the incident, transmitted, and reflected beams, respectively. Dividing equation (2.26) by $I_i A_i$ and using equation (2.22) and the fact that $A_i = A_r$, we get the ratio

$$\frac{I_t A_t}{I_i A_i} = 1 - \frac{I_r}{I_i} = 1 - R^2 \quad (2.27)$$

Figure 2.4 An example of a wave with pressure p_i and particle velocity u_i , striking an interface at normal incidence, resulting in transmitted and reflected waves, (after Christensen [18]).

2.5 Transducers

At the heart of all the medical ultrasonic instruments used to generate and receive ultrasound waves are elements which display the property of piezoelectricity. The piezoelectric effect has two complementary attributes.

(a) When a pressure is exerted tending to squeeze the element, an electrical voltage develops between the two opposite faces. When there is no pressure, there is no voltage and when the pressure is reversed in direction, the voltage is also reversed in polarity. The voltage developed is directly proportional to the pressure. Furthermore, if the pressure is alternating, that is cyclically or sinusoidally changing in polarity, the voltage developed follows the same pattern and is also alternating.

(b) If, on the other hand, a voltage from an external voltage source is connected across the element, its thickness changes, that is, the element is deformed or strained. The magnitude of the strain is directly proportional to the voltage applied. When the voltage is reversed in polarity the strain is also reversed in polarity. If the voltage applied is an alternating voltage, so also is the resulting strain, and that strain alternates in step with applied voltage.

Thus, the piezoelectric effect has a number of reciprocal aspects. The property described in (b) above, may be exploited to generate ultrasound. If the applied alternating voltage has a frequency of 1 MHz, then the element vibrates at 1 MHz, and ultrasound of that frequency is generated. The property described in (a) above may

be utilised to detect or receive an ultrasound wave. If such a element is placed in an ultrasound wave it experiences an alternating pressure of the frequency of the ultrasound. As a result an alternating voltage of the same frequency is created across the element disc. If means are available to display or record that voltage, one obtains a record of the ultrasound wave. Thus, property (b) is the ultrasound-generating aspect of the effect, while property (a) is the ultrasound-detecting aspect of the piezoelectric effect.

Certain materials that can be artificially produced display piezoelectricity. Such materials as barium titanate, lead zirconate titanate (PZT), lead titanate and lead metaniobate, all can have piezoelectric properties induced in them by suitable treatment. Certain semicrystalline polymers, such as polyvinylidene fluoride, PVDF, may also be made piezoelectric by stretching and polarizing them in a strong electric field during fabrication. Single crystals of quartz, rochelle salts and tourmaline also have been used widely, Hussey [19].

2.6 Continuous Wave Excitation of Transducer

If a voltage generator applies an alternating voltage across the transducer of the form $v = v_0 \cos \omega t$, then pressure waves produced will be continuous sinusoidal-type waves. These waves will propagate inside the element with a phase velocity c_t (phase velocity in transducer material) and will reflect from the front and back faces of the element. For the maximum output ultrasound intensity, that is, maximum

coupling of the electrical input power to a medium in contact with the transducer, the frequency of this alternating voltage must match the resonant frequency of the crystal, as determined by the thickness of the element.

The lowest frequency to satisfy the resonance condition is called the fundamental frequency of the element, and at this frequency a crystal half-wavelength fits inside the cavity. Figure 2.5 shows two waves which match both the boundary conditions and the excitation requirement. For a transducer of thickness L , the fundamental frequency f_1 will have a wavelength λ_1 inside the transducer such that

$$\lambda_1 / 2 = L \quad (2.28)$$

since $\lambda_1 = c_1 / f_1$, where c_1 is the compressional wave velocity in the transducer material, then

$$f_1 = c_1 / 2L \quad (2.29)$$

This mode, continuous wave (CW), was used for zone lens studies.

2.7 Pulsed Excitation of Transducer

A transducer may be pulse excited if the electrical input to the transducer is a sharp impulse of voltage, such as that obtained by rapidly discharging a capacitor through the transducer crystal. The pressure wave radiated by the transducer will take the form. : natural mechanical frequency of the transducer. The voltage pulse may be either negative or positive with respect to ground. Figure 2.6 shows the example of a positive voltage pulse and the resultant pressure waveform from the transducer.

Figure 2.5 Simplified sketch of transducer faces shows that an odd number of half-wavelength must fit between transducer faces, (after Christensen [18]).

Figure 2.6 The pressure waveform radiated by a transducer excited by a sharp impulse of voltage, (after Christensen [18]).

2.8 Beam Pattern

This discussion also follows the development given by Christensen [18]. The pressure wave that propagates from the face of an unfocused transducer generally maintains the approximate lateral dimensions of the transducer for a certain distance, but natural divergence begins to spread the transverse extent of the beam at larger distances so that the beam takes on a diverging nature. In the region near the transducer (*the "near field"*), the beam has many amplitude and phase fluctuations due to interference between the contributing waves from all parts of the transducer face, whereas in the region further from the transducer (*the "far field"*), the beam profile is much more uniform and well behaved. To solve for the radiation pattern from an ultrasonic transducer one may consider the geometry of the problem as in Figure 2.7; a circular coordinate system is initially assumed. The coordinates of the source points in the plane of the transducer face are denoted ρ and θ , and the coordinates pointing to the observation point where the pattern is sought are denoted r and ϕ . The distance from the source points to the observation point is given by r' . For circularly symmetric situations no generality is lost by letting the observation points lie on the x_1 axis. From the geometry in Figure 2.7

$$r' = (r^2 + \rho^2 - 2r\rho \cos\theta \sin\phi)^{1/2} \quad (2.30)$$

Figure 2.7 The general coordinates for solving for the radiation pattern from an ultrasound transducer, (after Christensen [18]).

To analyze the observed radiation pattern, we rely upon Huygen's principle, which states that the radiation pattern from a general extended source can be constructed by considering the source as an appropriately weighted collection of point sources, each radiating outwardly propagating spherical waves. To get the complete radiation pattern, the contributions of all spherical waves from all point sources comprising the transducer are added (magnitude and phase) at the point of observation. This decomposition of the complex problem into a summation of simpler parts (i.e., spherical waves radiating from point sources) is allowed because the wave equation is a linear equation in the pressure variable. Each point on the transducer face, then, is assumed to be the radiator of a spherical pressure wave, the form of which is

$$dp = \frac{kZ_o}{2\pi r'} \cos(\omega t - kr' + \frac{\pi}{2}) ds \quad (2.31)$$

where dp is the incremental pressure contribution at the observation point due to spherical wave from a point source of incremental area ds , k is the propagation constant of the wave ($k=2\pi/\lambda$), Z is the acoustical impedance of the intervening medium, and r' is the distance from source to observation point as given by equation (2.30). The pressure decreases as a function of $1/r'$ away from the point source consistent with the $1/r^2$ dependence of power density expected from the conservation of energy principle applied to a diverging spherical wave. In obtaining Equation (2.31), the transducer face was assumed to be vibrating with a sinusoidal velocity of $u = u_o \cos(\omega t)$ perpendicular to the $\rho - \theta$ plane.

The total pressure at the observation point is the integral of the incremental pressures:

$$p = \int_{\text{source}} dp \quad (2.32)$$

Assuming all portions of transducer face are oscillating with the same velocity and are in phase with each other, as would be the case for a rigid, piston-like transducer, Equations (2.31) and (2.32) may be combined to give

$$p = \frac{kZu_o}{2\pi} \int_{\text{source}} \frac{\cos(\omega t - kr' + \pi/2)}{r'} \rho \, d\rho \, d\theta \quad (2.33)$$

where $\rho \, d\rho \, d\theta$ has been substituted for ds . For a general transducer shape and for an arbitrary observation point, this equation is quite difficult to evaluate and usually requires a computer solution. But it may be evaluated for some simple cases, as shown below.

2.8.1 Near-Field Pattern (on-axis) of a Circular Transducer

Consider the transducer to be a circular disc of radius a . In the near-field region, r' is not large enough to allow a mathematical simplification of its form, so equation (2.33) is still too complex for a general solution. We therefore restrict our observation points to be on the z axis, such that $\sin \phi = 0$ and $r = z$. Equation (2.30) then reduces to

$$r' = \sqrt{\rho^2 + z^2}$$

Figure 2.8 shows the geometry for this special case.

Substituting for r' in equation (2.33) gives

$$p(z,t) = \frac{kZu_o}{2\pi} \int_0^a \frac{\cos(\omega t - k \sqrt{\rho^2 + z^2} + \pi/2)}{\sqrt{\rho^2 + z^2}} \rho d\rho \int_0^{2\pi} d\theta$$

Straightforward integration leads to

$$\begin{aligned} p(z,t) &= -Zu_o [\sin(\omega t - k \sqrt{a^2 + z^2} + \pi/2) - \sin(\omega t - k z + \pi/2)] \\ &= Zu_o [\cos(\omega t - k z) - \cos(\omega t - k \sqrt{a^2 + z^2})] \end{aligned} \quad (2.34)$$

This result for the on-axis pressure amplitude has a very interesting interpretation. Note that the first term in the equation, $Zu_o \cos(\omega t - kz)$, is just the familiar form for a pressure wave that appears to be coming from the centre of the transducer, whereas the second term, $Zu_o \cos[\omega t - k(a^2 + z^2)^{1/2}]$, which subtracts from the first, appears to be a wave coming from a point at the edge (*radius* = a) of the transducer. The combination of these two waves, with phases that change at different rates as z varies, provides the destructive and constructive interference pattern which produces the irregularities found in the near field.

A plot of the pressure obtained from equation (2.34) and shown in Figure 2.9, reveals the rapid variation of on-axis pressure in the near field of a circular transducer. Note that there are many points in the near field where the pressure

Figure 2.8 Geometry for calculating the near-field on-axis pressure field from a circular transducer of radius a and diameter D , (after Christensen [18]).

Figure 2.9 Variation of the magnitude of on-axis pressure field from a circular transducer of diameter D . This is a plot of the absolute magnitude of equation (2.34) at one particular time, $t=0$, and is the envelope of the oscillating pressure. The transition point from the near field to the far field is defined as the position of the furthest maximum. Beyond that point the field decreases monotonically, (after Christensen [18]).

actually goes to zero (complete destructive interference) and that the rapidity of the spatial oscillation of the pattern decreases as one moves further away from the face of the transducer. In fact, at large distances from the face of the transducer, the resultant pressure amplitude is no longer oscillatory but behaves as a slowly decreasing ($1/z$) field; this is the far field. Before the point of divergence of the beam, it is described as the "near field", or "Fresnel zone", and the diverging part of the beam is the "far field", or "Fraunhofer zone", Hussey [19].

To mark the transition from near-field to far-field behaviour, it is reasonable to choose the on-axis point where equation (2.34) has its last maximum for increasing z . This is the value of z for which the phase difference between the first cosine term and the second cosine term in equation (2.34) is just equal to π , so both terms are positive and the two terms add. Thus, if the transition point is denoted z_R , then

$$k(a^2 + z_R^2)^{1/2} - kz_R = \pi \quad (2.35)$$

Since $z_R \gg a$ for a transducer many wavelengths in radius, the radical in equation (2.35) may be approximated as

$$(a^2 + z_R^2)^{1/2} = z_R + a^2 / 2z_R$$

Then equation (2.35) becomes

$$kz_R + k a^2 / 2z_R - k z_R = \pi$$

Rearranging yields

$$z_R = a^2 / \lambda = D^2 / 4\lambda \quad (2.36)$$

2.8.2 Far-Field Pattern of an Ultrasound Transducer

When the beam is observed at a large distance from the transducer, simplifications can be made in the general equation (2.33) that allow the field to be calculated at any point (off-axis as well as on-axis) in the plane of observation. The approximations appear at two places in equation (2.33). First, in the far-field the magnitude of r' term which appears alone in the denominator of the integrand will not differ appreciably from r over the range of the source integration, since r is much greater than the source dimension. This r' is therefore set equal to r (a constant) with respect to the integration variables) and is brought out of the integral.

Second, the r' term in the argument of the cosine also may be approximated, but since this r' is multiplied by $k (=2\pi/\lambda)$, and since λ is small at ultrasonic frequencies (making k large), this approximation cannot be allowed to be as rough as letting $r' = r = \text{constant}$; the phase term kr' may vary by several radians over the source integration, causing several oscillations of the cosine term. To preserve this interference effect in the integration, only a partial simplification of r' from equation (2.30) is made, known as the *Fraunhofer approximation*. If the observation distance is far enough away from the source that the source appears small compared to the observation length, then $r \gg \rho$ and equation (2.30) may be approximated by

$$r' \approx r - \rho \cos \theta \sin \phi \quad (2.37)$$

Putting equation (2.37) into the phase term of equation (2.33) and letting $r = r$ in

the denominator as discussed above gives

$$\begin{aligned} p(\phi, r, t) &= \frac{kZu_0}{2\pi r} \int_{\text{source}} [\cos\omega t - kr + k\rho \cos\theta \sin\phi + \frac{\pi}{2}] \rho d\rho d\theta \\ &= K_1 \int_{\text{source}} \cos[\psi(t) + k\rho \sin\phi \cos\theta] \rho d\rho d\theta \end{aligned} \quad (2.38)$$

where

$$K_1 = kZu_0 / 2\pi r$$

and

$$\psi(t) = (\omega t - kr + \frac{\pi}{2})$$

K_1 and $\psi(t)$ are constants with respect to integration over the source coordinates ρ and θ . The result of this integration will depend upon the particular shape of the transducer.

For a circularly symmetric source, the limits of integration become simply

$$p(\phi, r, t) = K_1 \int_0^a \int_0^{2\pi} \cos[\psi(t) + k\rho \sin\phi \cos\theta] d\theta \rho d\rho$$

Using the trigonometric identity $\cos(A+B) = \cos A \cos B - \sin A \sin B$ gives

$$\begin{aligned} p(\phi, r, t) &= K_1 \int_0^a [\cos\psi(t) \int_0^{2\pi} \cos(k\rho \sin\phi \cos\theta) d\theta \\ &\quad - \sin\psi(t) \int_0^{2\pi} \sin(k\rho \sin\phi \cos\theta) d\theta] \rho d\rho \end{aligned} \quad (2.39)$$

The last integral in this equation is zero since the sine term is an odd function of the cyclical argument $(\cos\theta)$ as θ ranges from 0 to 2π . The other integral over θ is of the form which results in a Bessel function, as given in reference texts [20,21]

on Bessel functions:

$$\int_0^{2\pi} \cos(x \cos \theta) d\theta = 2\pi J_0(x)$$

where J_0 is the Bessel function of the first kind with order zero. Therefore, equation (2.39) becomes

$$p(\phi, r, t) = 2\pi K_1 \cos \psi(t) \int_0^a J_0(k\rho \sin \phi) \rho d\rho \quad (2.40)$$

This integral, in turn, can be evaluated by the relation

$$\int x J_0(x) dx = x J_1(x)$$

where J_1 is the Bessel function of the first kind with order 1. Then, equation (2.40) becomes

$$p(\phi, r, t) = \pi a^2 K_1 \cos \psi(t) \left[\frac{2J_1(ka \sin \phi)}{ka \sin \phi} \right] \quad (2.41)$$

The instantaneous radiated power density pattern may be found from $I = p^2 / Z$, and reinserting the previous definitions for K_1 and $\psi(t)$ yields

$$I(\phi, r, t) = \frac{\pi^2 a^4 u_0^2 Z \sin^2(\omega t - kr)}{\lambda^2 r^2} \left[\frac{2J_1(ka \sin \phi)}{ka \sin \phi} \right]^2 \quad (2.42)$$

Some interesting observations about the far-field radiation pattern from a circular transducer may be obtained from equation (2.42). First, note that the power density decreases as $1/r^2$ in this region, as would be expected when the measurements are made far enough away that the source appears as a small radiator of diverging waves. More importantly, the distribution with respect to angle behaves according to the term in the square brackets, the so-called *directional factor* :

$$H_c(\phi) = \left[\frac{2J_1(ka \sin\phi)}{ka \sin\phi} \right] \quad (2.43)$$

To obtain a feeling of the shape of this far-field pattern, it may be plotted on an observation screen a distance z away from the transducer. If the angles of divergence of the beam are not too great, the small angle approximation

$$\sin \phi \approx x_1 / z \quad (2.44)$$

may be used, where x_1 is the coordinate in the plane of observation; refer to Figure 2.7. Then, the directional factor equation (2.43) may be written in terms of distance on the observation plane:

$$H_c(x_1) = \left[\frac{2J_1(kax_1/z)}{kax_1/z} \right] \quad (2.45)$$

The square of this term is called "*Airy Pattern*" , Figure 2.10, and gives an indication of the extent of the power density pattern at a distance z from the transducer. Due to the denominator of $H_c(x_1)$ and the behaviour of J_1 , the power density drops off rapidly as x_1 increases from the centre of the pattern. Also, there

are repetitive zeros and side peaks as the Bessel function J_1 oscillates with the increasing arguments.

The great majority of power is contained in the central (main) lobe of the pattern between the first zeros on either side of this central peak. However, some power is found in the side lobes which neighbour the main lobe. The extent of the main lobe may be defined as occupying the area between the first zeros; these zeros occur at

$$J_1(\pm 3.83) = 0 \quad (2.46)$$

or

$$x_1 = \pm 3.83 \, z / ka$$

as shown in Figure 2.10. Note that the width of the main lobe increases linearly with distance z in the far-field region.

Returning now to the angular dependence of the far-field radiation pattern, equation (2.43) shows that the pattern may be considered to be a circularly symmetric function of the angle ϕ via the term $\sin \phi$; this equation is valid even for large ϕ .

The angular position of the first zero defines the amount of divergence (*half-angle*) ϕ_d of the main lobe as it propagates from the source; from equation (2.46),

$$\sin \phi_d = 3.83 / ka$$

or

$$\phi_d = \sin^{-1}(0.61 \, \lambda / a) \quad (2.47)$$

Note the inverse relationship in equation (2.47) between ϕ_d and the transducer

radius a . When a is a large number of wavelengths, the far-field beam is highly directed; conversely, when a is small, the beam spreads considerably as it propagates from the transducer [18]. In fact, when a is approximately one-half a wavelength (i.e., the diameter is one wavelength) or smaller, the half-angle of divergence is greater than 90° and the beam appears to be radiating hemispherically more or less isotropically from a point source.

Figure 2.10 The far-field power density pattern, " *Airy Pattern* ", observed at a distance z from a circular transducer of radius a , (after Christensen [18]).

CHAPTER 3

Focusing with simple and zoned lenses

3.1 Acoustic lenses

There is an analogy between optics and acoustics. Therefore one would expect that optical devices such as lenses and reflectors would have their acoustical counterparts [8].

If the acoustic wavelength is short enough, a natural approach to solving certain problems is geometrical acoustics would be to use the ray technique, a simple method of geometrical optics. However, it must be remembered that there is no perfect

analogy between geometrical optics and geometrical acoustics. For instance, in isotropic solids an obliquely incident acoustic wave generates three modes (longitudinal, shear and surface acoustic wave), while in optics only the transverse mode exists. The existence of two modes in an acoustic lens may produce a double focus. Also, interference phenomena are much more pronounced in geometrical acoustics. For instance, acoustic waves emitted from parts of a lens separated by few millimetres interfere strongly at the focal point. In optics there may be several hundred wavelengths difference in phase between parts of an optical beam a few millimetres apart. In acoustics, the imperfections of the lens, either on the surface or in the volume, may be on the order of a fraction of the wavelength, thus causing no interference at the focal point.

As in optics, concave reflectors, zone plates, prisms, and lenses are used in acoustics [8,22] as well. Acoustic lenses have wide applications as acoustic energy concentrators. Two types of acoustic lenses [23] can be distinguished: immersion-type lenses, where a liquid surrounds a lens made of solid material, Figure 3.1(a), and direct contact lenses also called angled lenses, in which only solid materials are employed, Figure 3.1(b). Acoustic lenses can also be made with liquid materials. In this case a shell made of acoustically thin walls is used to define the shape of the lens.

Solid lenses are usually made of lucite, sapphire, quartz, a few other materials have been tried.

For immersion lenses, the acoustic velocity in the lens is generally higher than the acoustic velocity of the surrounding liquid. This is the opposite of what happens

in optics for the corresponding light velocities. Therefore, acoustic converging lenses are concave.

3.2 Focal Length of a Plano-Concave Lens

Consider a plano-concave lens, shown in Figure 3.2, where the concave side is made with a curvature corresponding to the spherical radius R . For plane acoustic waves incident from the left, the focal distance f is determined by the requirement that at the focus F all rays must have equal phase. Requiring that rays I and II have zero phase difference at F , one may write the corresponding equations for rays I and II as follows:

$$\text{Path I : } \frac{f}{c_m} + \frac{s}{c_L} \quad (3.1)$$

$$\text{Path II : } \frac{T}{c_L} + \frac{p}{c_m} \quad (3.2)$$

From geometry of Figure 3.2 one may write:

$$p = [(f - T + s)^2 + r^2]^{1/2} \quad (3.3)$$

and

$$r^2 = R^2 - (R - T + s)^2 = 2R(T - s) - (T - s)^2 \quad (3.4)$$

Putting equation (3.4) into equation (3.3) gives

$$p = [(f - T + s)^2 + 2R(T - s) - (T - s)^2]^{1/2} \quad (3.5)$$

Equation (3.5) can be substituted into equation (3.2) to give

$$\text{Path II : } \frac{T}{c_L} + \frac{1}{c_m} [(f - T + s)^2 + 2R(T - s) - (T - s)^2]^{1/2} \quad (3.6)$$

The simultaneous solution to equations (3.1) and (3.6) is given by:

$$\frac{f}{c_m} = \frac{T - s}{c_L} + \frac{1}{c_m} [(f - T + s)^2 + 2R(T - s) - (T - s)^2]^{1/2} \quad (3.7)$$

or

$$f = \frac{R}{1 - c_m / c_L} - \frac{(T - s)(c_m / c_L)^2}{2(1 - c_m / c_L)} \quad (3.8)$$

For small apertures, $(T - s) \approx 0$, and

$$f = \frac{R}{1 - c_m / c_L} \quad (3.9)$$

As the aperture increases, because of spherical aberration, as seen from equation (3.8), the focal point moves toward the lens and the focal area is axially widened [24].

Figure 3.1. (a) Immersion type lens. (b) Angled lens, (after Ristic [24]).

Figure 3.2 Plano-concave lens made with a spherical surface of radius R , (after Ristic [24]).

3.3 Beam Pattern in the Focal Plane

Lenses have the property of transforming angles into position. That is, all rays entering the lens at a common angle ϕ will get directed to a radius x_f on the focal plane as shown in Figure 3.3. Under the small angle approximation, geometry gives the transformation relationship as

$$\sin \phi \approx x_f / f \quad (3.10)$$

Therefore, a lens of focal length f placed in front of the beam from a circular transducer whose radiation pattern is given by equation (2.43) will transform the far-field angular distribution into a spatial distribution on the focal plane via the transformation of equation (3.10). Making this substitution into equation (2.43) and squaring the result yields the spatial distribution of the intensity at a focused spot from a circular transducer of radius a :

$$H_c^2(x_f) = \left[\frac{2J_1(kax_f / f)}{(kax_f / f)} \right]^2 \quad (3.11)$$

and the *focused pattern* looks exactly like the far-field pattern of Figure 2.10, except that it is scaled down by an amount f / z [18]. Figure 3.4 shows how the focused spot would appear face-on.

Figure 3.3 A lens has the property of transforming angles into position on the focal plane. (after Christensen [18]).

Figure 3.4 The greatly magnified pattern of a focused spot from a lens of focal length f . (after Christensen [18]).

3.4 Size of Focal Spot

The focused spot has a dense central portion (corresponding to the main lobe) surrounded by minor rings (the side lobes). The diameter of the central portion is defined as previously: the distance between the first zeros bounding the main lobe. From equation (3.11) the radius of the first zero is found at

$$x_1 = \frac{3.83 f}{ka} = \frac{0.61 f \lambda}{a}$$

or, put in terms of original beam (transducer) diameter $D = 2a$, the diameter between first zeros is the focused spot diameter $d = 2x_1$:

$$d = 2.44 \left(\frac{f}{D} \right) \lambda \quad (3.12)$$

Figure 3.5 defines the quantities entering equation (3.12).

The effects of divergence are manifested in these relationships. In equation (3.12) the larger the diameter D of the transducer, the smaller is the tendency of divergence to expand the beam, and the smaller the spot of focus. Also, the further away the position of focus f , the greater is the effect of divergence, leading to a larger d .

The ratio in the parentheses in equation (3.12) is known as the "*f-number*" of

the lens; and due to practical limitations such as spherical aberration, it is difficult to fabricate a high quality lens whose *f-number* is much smaller than unity. Therefore, as a rule of thumb, it can be said that the smallest possible focused spot is on the order of the wavelength of radiation used.

Not only is it impossible to focus to an infinitely small spot, it may be impossible to get any narrowing at all in the beam diameter if the attempted focal distance is too far away. Equation (3.12) shows that d will be greater than D if

$$f > \frac{D^2}{2.44 \lambda} \approx z_R \quad (3.13)$$

or, in other words, no focusing occurs if the focal length of the lens is greater than about the transition distance. Thus, it may be said that focusing is only possible at distances within the near field, not in the far field of a transducer.

3.5 Depth of Focus

There is one disadvantage to tight focusing of the beam. Although it improves lateral resolution for reflecting objects located in the plane of focus, points in planes either nearer or further away than the focal length are compromised because the beam is somewhat larger than d on either side of the focal plane. The problem gets worse with decrease in the focused size, as shown in Figure 3.6.

The axial distance over which the beam maintains its approximate focused size is termed the depth of focus. To obtain an estimate of this distance, note that the beam shapes on both sides of the focal point are mirror images of one another, reflected about the focal plane. The beam behaviour on one side of this plane, from the focus outward, has the same general characteristics that of a beam propagating from an initially planar wavefront of a approximately equal to the beam diameter. Therefore, it stays approximately collimated within the transition distance z_R . Applied to the situation here, the transition distance of equation (2.36) becomes

$$z_{R,d} = d^2 / 4\lambda$$

the depth of focus may be estimated to be twice this distance due to symmetry about the focal plane:

$$\text{Depth of focus} \approx d^2 / 2\lambda \approx 3(f / D)^2 \lambda \quad (3.14)$$

where equation (3.12) was used to get the last result.

The tradeoff between focused size and depth of focus sometimes dictates a compromise lens design. For example, in fixed-focus systems, the lens may be purposely given a nonspherical surface to cause the focused spot size to be larger than the theoretical limit, thereby increasing the depth of focus [18].

Figure 3.5 A lens will focus the beam to a small spot, but the size d of the focused spot depends upon f , D , and λ according to equation (3.12), (after Christensen [18]).

Figure 3.6 The depth of focus describes the longitudinal distance over which the beam maintains its approximate focused size. It gets shorter for a tightly focused beam, (after Christensen [18]).

3.6 Zone Lenses

The idea of zoned lenses is a natural consequence of wave considerations. The primary point of zoned lenses is to have a lens which does not become excessively thick, since most potential lens materials are rather strong absorbers (typically 1 to 3 *dB/cm*). Other reasons, such as field shaping, or a frequency dependent focal length might be considered. In any case, the fundamental point is that there must be constructive interference between the contributions of the zones to produce the desired result [17].

Acoustic zone lenses have a long history [8]. Before we discuss previous designs of acoustic zone lenses, we will briefly discuss Fresnel zone lenses in optics and microwave technology.

3.6.1 Fresnel Zone Lenses in Optics and Microwave

Consider the propagation of a spherical wavefront in a Fresnel lens or half-period zones shown in Figure 3.7. In optics one may add up the secondary wavelets arriving at a point P and thus obtain the unobstructed primary wave. As illustrated, the wavefront was divided into a number of annular regions. The boundaries of the various regions correspond to the intersections of the wavefront with a series of spheres centred at P of radius $r_o + \lambda/2$, $r_o + \lambda$, $r_o + 3\lambda/2$, and so forth. These are

the Fresnel or half-period zones. Since successive Fresnel zones tend to nullify each other, this suggests that one will observe a tremendous increase in irradiance at P , if one removes either all the even or all the odd zones. To calculate the radii of the zones shown in Figure 3.8(a) refer to Figure 3.8(b). The outer edge of the m th zone is marked by the point A_m . By definition, a wave that travels the path $S-A_m-P$ must arrive out of phase by $m\lambda/2$ with a wave that traverses the $S-O-P$, that is,

$$(\rho_m + r_m) - (\rho_o + r_o) = m\lambda/2 \quad (3.15)$$

Clearly $\rho_m = (R_m^2 + \rho_o^2)^{1/2}$ and $r_m = (R_m^2 + r_o^2)^{1/2}$. Expand both these expressions using the binomial series. Since R_m is comparatively small, retaining only the first two terms yields

$$\rho_m = \rho_o + R_m^2/(2\rho_o) \quad \text{and} \quad r_m = r_o + R_m^2/(2r_o)$$

Finally, substituting into equation (3.15), one obtains

$$(1/\rho_o + 1/r_o) = m\lambda/R_m^2 \quad (3.16)$$

Under plane-wave illumination ($\rho_o \rightarrow \infty$), and equation (3.16) reduces to

$$R_m^2 = mr_o\lambda \quad (3.17)$$

Equation (3.16) has a form identical to that of the thin-lens equation, which is not merely a coincidence, since S is actually imaged in converging diffracted light at P [21]. Accordingly, the primary focal length is said to be

$$f_1 = R_m^2/m\lambda \quad (3.18)$$

In microwave applications, dielectric lenses of large diameter are quite heavy and have significant attenuation loss. These disadvantages can be reduced by employing the "stepped" or "zoned" construction shown in Figure 3.9(a), but surface

Figure 3.7 Propagation of a spherical wavefront in a Fresnel or half-period zones (after [21]).

Figure 3.8 (a) zone plate (b) zone plate geometry (after[21]).

matching of the stepped face is likely to be difficult, and some power is scattered into unwanted sidelobes at discontinuities caused by the "steps" [25].

An alternative is the "fresnel zone plate lens". In the plane OPQ of Figure 3.9(b), the distance from the source S to points on a circle of radius r_m is equal to SP (denoted by f) plus $m\lambda/2$, where m is an integer:

$$r_m^2 = mf\lambda + m^2 \lambda^2/4 \quad (3.19)$$

At centimetre and millimetre wavelengths, a reasonably efficient zone-plate lens of focal length f can be produced by making the electrical path through the alternate annuli having $r_{m-1} < r < r_m$, $r_{m+1} < r < r_{m+2}$, etc., one half-wavelength longer (or shorter) than that through the intermediate annuli with $r_m < r < r_{m+1}$, etc. Figure 3.8(c) shows that this is achieved if annular grooves of the appropriate widths and depth

$$d' = \lambda/[2(n-1)] \quad (3.20)$$

are machined into the surface of the dielectric sheet whose refractive index is n . This form of zone-plate lens produces a signal intensity at a distant point which is four times greater than that from the optical zone-plate, in which the intermediate zones are made opaque: but because there is a 180° phase variation across each zone the efficiency is still about $4dB$ less than that of an "ideal lens" which gives perfect phase-correction across its aperture. This type of lens does also have a rather limited operating bandwidth [25].

Figure 3.9 Stepped dielectric and Fresnel zone plate lenses, (a) Stepped dielectric lens; (b) Geometry of the Fresnel zone plate; (c) Half-period zone plate lens. (after garham [25]).

3.6.2 Acoustic Zone lenses

In acoustic, very much as in optics, a Fresnel zone plate can be made to concentrate the beam into a small area. Before we discuss the acoustic zone lens which is designed in this study, we will briefly discuss the Fresnel zone or zone lenses that already designed by different investigators.

Tamoczky [8], designed two types of zone lenses, the first was a Fresnel zone plate, the same as for optics. Figure 3.10 shows the wavefront leaving the plate is divided into circles centred on P , and with radii r_o , $r_o + \lambda/2$, $r_o + 2\lambda/2$, ..., . From every second ring of the in-phase wavefront, waves with a phase difference of $\lambda/2$ arrive at P where they reinforce one another. With the unwanted rings covered, one obtains a reinforcement at P , which may be regarded as a focus. The radii of successive rings are derived from geometry. The relation simplifies to

$$R_m^2 = (m\lambda r_o) / [1 + (r_o/\rho_o)] + m^2 \lambda^2 / \{4[1 + (r_o/\rho_o)]\} \quad (3.21)$$

Tamoczky reported that this zone plate lens had a small gain because of the damping effect of covered rings.

The second zone lens of Tamoczky [8] was a zone lens with a series of flat rings whose thicknesses differ from one another by $\lambda/2$, Figure 3.11. Sound rays starting from rings with the radii r_n reach F in phase with the centre ray if the relationship

$$\frac{f}{c_1} = \frac{n\lambda}{2c_2} + \frac{\lambda}{c_1} \sqrt{r_n^2 + (f - \frac{n\lambda}{2})^2} \quad (3.22)$$

holds [8]. Where c_1 and c_2 are the velocities in the environment and the lens respectively. By selecting suitable r_n the waves from several rings may be made to arrive with the same phase. The focal length is given by

$$f = \frac{r_n^2}{n\lambda[1 + (c_1/c_2)]} + \frac{n\lambda}{4}(1 + c_1/c_2) \quad (3.23)$$

The radii of the individual rings are determined for a given focus [8]. As shown from Figure 3.11 and Figure 3.12 this zone lens has the same drawback of having as large a thickness at the rim as simple lens and therefore possibility of crack formation at high intensity ultrasound near the rim [26].

In 1979, (Wess et al) designed an acoustic Fresnel zone lens used in ultrasonic imaging. The lens is composed of concentric zones of different width according to the Fresnel zone plate geometry with radii given by

$$R(m) = [(f + n\lambda)^2 - f^2]^{1/2} \quad m=0,1,2, \dots \quad (3.24)$$

with f being the focal length of the zone plate (as well as the focal length of the final Fresnel lens) [29]. In order to achieve focusing properties in such a geometrical structure usually every second zone is covered by an opaque shield. By introducing a $\lambda/2$ phase shift between adjacent zones instead of covering every second zone the full aperture area is used. Although such a phased Fresnel zone plate is faster (the effective aperture is doubled) there do exist higher diffraction orders giving rise to false images and a diminished efficiency of the focusing device [29]. Each ring

Figure 3.10 Wavefront leaving a zone plate is divided into circles centred on P whose radii increase by increments of $\lambda/2$, (after Tarnoczy [8]).

shaped zone is profiled as being a part of spherical lenses with a common focal point F [29]. Figure 3.13 shows such a Fresnel zone lens profile calculated for a polystyrol lens in water for an ultrasonic frequency of 1.6 MHz ($\lambda = 0.9275\text{ mm}$) [29]

In 1981, Szilard and Kidger, designed a spherical ultrasonic Fresnel lens and pointed out that in ultrasonics, as distinct from optics, we are dealing with waves in a range three or four orders of magnitude longer, monochromatic and coherent. These differences have significant consequences. As the lens profile undergoes steps, the path differences of the waves, which causes refraction, also undergoes steps. These steps have to obey the same rules as the zone plates, they must be even multiples of a half wavelength (integer multiple of a wavelength), i.e. the foci of the "ordinary Fresnel lens" and the "zone plate" must coincide. Otherwise only part of the energy will meet at the original focus [30]. The lens was made from perspex with focal length of 7 cm, 6 cm diameter and the steps on each plano-concave "half" lens corresponded to 2 MHz , Figure 3.14, [30]. They reported that the usefulness of the lens is strongly dependent on the materials envisaged for a particular lens and in certain cases it may prove advantageous, especially for cylindrical lenses when the bandwidth is much greater [30].

On the basis of above discussion, Szilard 1982, designed a cylindrical ultrasonic Fresnel lenses, Figure 3.15. The difference between the behaviour of spherical and cylindrical Fresnel lenses was examined in view of the special applications of cylindrical lenses in sonar systems for modifying the beam shapes of arrays [31]

After Szilard 1982, with the same analogy as [31], Warnes 1982, made a

diverging cylindrical acoustic Fresnel lens for a scanning sonar transmitter, Figure 3.16. Warnes showed that at low frequencies the step height becomes very large (about 55 mm for 60 KHz, for example) and so concluded that a Fresnel lens offers little advantage over a simple lens, unless antiphased zones are used. This constraint is especially pronounced if wide beams are used [32].

Following Tarnoczy's work, acoustic Fresnel lenses were designed mostly for imaging ultrasound or other special cases, for example, cylindrical sonar scanner. In all above cases the problem of mode conversion was totally ignored [33-43].

When an incident compressional wave strike a boundary at a nonzero angle, surface acoustic waves, reflected and transmitted shear waves will therefore generally be generated in addition to reflected and transmitted compressional waves. It should be noted that the surface acoustic waves and shear waves are existing only in solids, therefore, the portion of energy contributing to these waves eventually lost in the lens body as a heat.

In all acoustic lenses discussed above the "refracting surface" has been used to design either Fresnel zone lens or zone lenses. These extra surfaces of zones at the "refracting surface" of the lens increase the amount of energy converted to surface acoustic waves [37] and shear waves [39], which is eventually lost in the lens body and so increases the internal temperature. Therefore, Jones and Kwan (1985), recommended that to avoid mode conversion one should limit the number of refracting surfaces [41].

Figure 3.13 Fresnel lens profile, (after Wess [29]).

Figure 3.14 Ultrasonic Fresnel lens, (after Szilard [30])

In this study, a plano-concave lens was chosen and the plane side (non-refracting surface) was cut to make the steps in order to keep the mode conversion as small as possible.

In acoustic zone lenses, thickness steps are made at the point where one zone ends and the next begins. The size of step must be such that the sound vibrations which emerge from the lens from a given zone are in phase with the vibrations in the water from the adjacent zone. Because the most important factor in such a lens is that waves coming from different zones are in phase, therefore one may call the lens a zone lens.

The area of zones were equal in this study in order to have approximately equal amplitude contribution from different zones, but it is not necessary to have zones with equal area. The actual configuration of zone lens is shown in Figure 4.6

3.6.2.1 Step Size of Zone Lens

The essential feature of a zone lens is the step size of zones, the area of the zones are equal. The area of zones may be set with considerable freedom of choice. In the present work, the zones are chosen to have equal area, so as to give approximately equal contributions to the final focused beam. To determine the step size of a zone lens consider a plano-concave lens with two zones on plano side with equal area and a step size of Δx . The geometry of the problem is given in Figure 3.17. As shown in Figure 3.17 for plane acoustic waves incident from the left, one may write the corresponding equations for the acoustic path length of rays I and II as follows :

$$\text{Path I : } \frac{\Delta x}{\lambda_w} + \frac{x_1 - x_2}{\lambda_L}$$

$$\text{Path II : } \frac{\Delta x}{\lambda_L} + \frac{x_1 - x_2}{\lambda_L}$$

where λ_w and λ_L are wavelengths in water and plexiglass respectively and Δx is the step size of two adjacent zones.

For a minimum step size corresponding to 2π phase shift the acoustic path difference between ray I and II will be equal one. Subtracting *Path I* from *Path II* and putting the result equal to one (that corresponds to one wavelength acoustic path difference)

$$\Delta x \left(\frac{1}{\lambda_w} - \frac{1}{\lambda_L} \right) = 1 \quad (3.25)$$

Substituting values of λ_w and λ_L in equation (3.28) one may get the Δx , which is the step size of the zone lens.

Having λ_w and λ_L as 1.42 mm and 2.54 mm respectively, at 1.05 MHz frequency, equation (3.28) gives

$$\Delta x = 3.22 \text{ mm} \quad (3.26)$$

Figure 3.17 Simplified sketch of zone lens for the calculations of the step size Δx

CHAPTER 4

Experimental Set up and Procedures

The experiments described in this study were carried out at a frequency of 1.05 MHz, corresponding to a wavelength of 1.43 mm in water. This frequency is at the low end of the medical imaging range, about the middle of the ultrasound therapy range and at the high end of the physiotherapy range. The current interest is in therapy, so many of the considerations of imaging are not relevant. Efficiency and durability are of major importance.

This chapter describes experimental procedures and the components of the

equipment used to test the lens principles. This includes the water tank arrangement, transmitting, receiving systems and the lenses and the alignment system.

4.1 Mechanical Structure

4.1.1 Water Tank Arrangement

The water tank was made of fibre-glass, and was 60 cm long, 37 cm wide and 28 cm deep. Over the tank were one aluminium optical bench which spanned the length of the water tank (z-axis) and one motorized bridge at right angle to it. The bridge consisted of a pair of parallel horizontal rods which supported a threaded rod. The threaded horizontal rod moved a small carriage with a needle hydrophone holder attached to it. The mechanism moved the hydrophone horizontally so as to scan the width of the tank in the direction of the x axis.

The hydrophone holder had three degrees of freedom : x (along the width of the tank), y (vertical motion) and r (rotation around the y - axis). The transducer was supported by a saddle mounted on the aluminium optical bench. One translational stage and two rotational stages were attached to the saddle. They provided four degrees of freedom : z (along the optical bench and length of the tank), y (vertical motion "up & down"), r_1 (rotation around the y-axis), r_2 (rotation around the x-axis). The lenses were mounted on a micro bench which was in turn attached to the transducer holder.

To prevent any acoustic reflections off the sides of the water tank, pieces of sponge 44 mm thick and 120 mm high were placed against the wall of the tank. To reduce reflections from around the hydrophone holder itself, a small cone shaped sponge was used.

Figure 4.1 shows the conventions for directions in relation to the beam of the transducer and Figure 4.2 shows the water tank arrangement.

In order to keep the speed of ultrasound constant, the temperature of water was kept close to 24°C.

Figure 4.1 Conventions for directions in relation to the beam of a transducer.

Figure 4.2 Water tank arrangement.

4.2 Transmitting and Receiving System

4.2.1 Transmitting and Receiving System in the CW Mode

Figure 4.3 (a) and (b) show block diagrams of the transmitting and receiving electronic systems in a continuous wave (CW) mode. A transmitting transducer is driven by frequency generator (Hewlett-Packard Synthesizer model 3336C) and power amplifier. The transducer was PZT disk, with effective diameter $D \approx 32.1$ mm and of a 1.05 MHz centre frequency. The power amplifier was an ENI, A300-40PA. The receiving transducer, a broadband (0.5-10 MHz) miniature needle hydrophone, had a 0.6 mm active element diameter and was manufactured by Dapco, Vital 19T model 58118. Figure 4.5 shows the view of the transducer and the hydrophone. The latter was connected to an amplifier (Metrotec MR101 Receiver) and spectrum analyzer (Hewlett-Packard, 8553B RF section and 8552B IF section) working as a peak detector. The D.C. voltage applied to the transducer was read with a true RMS voltmeter (Fluke, model 8920A) and was kept at 5.0 volts. A motor drive (Gerald K. Heller Co., model 2T60-18) and a power supply (Hewlett-Packard Harrison 6205B Dual DC Power Supply) actuated the scanning motion. The spectrum analyzer and the drive were connected to a data acquisition system (Data scan 7010 controller and 7020 16 channel module). A 286-AT IBM compatible microcomputer was used to store and process the data. Software has been written to read the output of the ADC to the screen and store the data for further processing.

4.2.2 Transmitting and Receiving System in the Pulse Mode

Figure 4.4a and 4.4b show the block diagrams in the pulse mode.

The transducer was driven by an ultrasonic pulser (designed in the department). The needle hydrophone was connected to an amplifier (Metrotec MR101 Receiver) and an oscilloscope (Tektronix, type 454).

Figure 4.3 Block diagram of CW mode electronic system.

(a) Transmitting electronic system.

(b) Receiving electronic system.

Figure 4.4. Block diagram of Pulse Mode Electronic System.

(a) Transmitting Electronic System.

(b) Receiving electronic System.

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PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

Figure 4.5 A photo of transducer-lens assembly (a) and hydrophone (b).

4.3 Properties and Manufacture of the Lenses

A block of acrylic plastic, (lucite) was used to determine the speed of sound by the time of flight method in pulse mode ultrasound. The same method was used to determine speed of sound in water (24°C). The results were 1496 m/s $\pm$ 5 % and 2669 m/s $\pm$ 5 % for water and lucite, respectively. These data show good agreement with other reference data [44].

Five different plastic lenses were made, table 4.1. One of these was a plano-convex and others were plano-concave. The plano-convex lens was used to expand the beam but after a wavefront experiment in pulse mode it was decided not to use this lens because it introduced significant wavefront aberration. Table 4.1 shows the specification of all lenses and Figure 4.6 shows the actual configuration of lens III (simple) and IV (zone). The lenses were manufactured in the Science Technology Centre of Carleton University.

4.4 Experimental Procedure

Experiments were done in the water tank previously described, Figures 4.1 and 4.2. The transmitting transducer was mounted on an optical bench with one translational stage and two rotational stages. The receiving transducer (miniature needle hydrophone) was fixed to a motor drive which could scan the width of the tank (x axis).

Table 4.1* Specification of different lenses.

Type of Lens	Radius of Curvature(mm)	Thickness at Rim (mm)	Focal Length (mm)
Plano-concave (I)	64.5	10	147
Plano-concave (II)	64.5	14	147
Plano-concave (III)	46.75	26.7	105
Zone Lens (IV)	46.75	20.9	105
Plano-convex (V)	46.75	7.5	105

* All lenses were made from plexiglass and were of diameter 60 mm.

Figure 4.6 Actual configuration of lenses (mm), (a) Simple plano-concave lens (III), (b) Zone lens (IV).

4.4.1 Removal of Spurious Reflections from Sides of Water Tank and around Hydrophone

The beam pattern of the transducer was measured with the hydrophone scanning in the x direction at varying z distances. The results showed reflections from the sides of the tank. Sponge panels were used on all sides to suppress these effects. The experiment was done in pulse-mode.

An experiment investigating spurious reflections from the hydrophone was carried out in pulse-mode. It was found that small conical shape sponges placed around the needle hydrophone suppressed the reflections.

4.4.2 Computer Program for the Data Acquisition System

An interactive program was written in Basic language for our data acquisition system to do the following :

- 1- Read the hydrophone output and record the data on a disk file.*
- 2- Calibrate hydrophone signals and corresponding positions.*
- 3- Process the data.*
- 4- Produce hard copies.*

Although this software was able to plot the ultrasonic field pattern, the more versatile Grapher software was used to plot the graphs shown here. A copy of the original program is provided in appendix A.

4.4.3 Wavefront Experiments with and without Diverging Lens

A series of experiments was performed in order to expand the beam and compare the wavefronts of beams with and without the diverging lens. Two experiments in pulse-mode were done and as a result it was understood that the diverging lens introduces unacceptable aberrations into the system. Therefore it was decided not to use the diverging lens in further studies.

4.4.4 Alignment of Transmitting Transducer and Lenses

As mentioned earlier, lenses were mounted on the micro bench which in turn was attached to transducer holder. To align the lenses and transducer, a laser source was used. The procedure of alignment was as follows :

With no lens on the micro bench, a small flat mirror was attached to the centre of the transducer. The transducer was moved along optical bench in order to make the laser beam parallel with the axis of the transducer and mirror. With the help of a translational stage and two rotational stages the transducer was moved until the laser beam reflected from the mirror onto itself. Then a lens was put on the micro bench and its position was adjusted until the laser beam reflected from the mirror passed through the centre of the lens. The transducer and the lens were then mounted onto the optical bench over the water tank. Using the translational stage and two rotational stages on the transducer assembly one could align the receiving hydrophone along the transducer's acoustic axis.

CHAPTER 5

RESULTS

5.1 Near and Far-Field Plots without Lens

In this study, the water tank arrangement, alignment of transmitting and receiving transducer, and data acquisition system were tested. In order to align the transmitting transducer with receiving hydrophone, the procedure described in section 4.4.4 was repeated. The temperature of water in the tank was kept at 24°C.

Having aligned the transducer and hydrophone, with 10 mm distance between the two, the hydrophone was centred in the z axis with respect to the x and y axis by setting on the maximum signal. Then, the hydrophone was scanned in transverse direction, x axis, i.e. perpendicular to the beam direction. Figure 5.1 shows a plot of hydrophone signal against its position in a near field ($z=10$ mm) for a non-focused transducer of 32.1 mm effective diameter with 1.05 MHz centre frequency. For these conditions the far field boundary is at ≈ 181 mm. The far field pattern of the transducer was obtained for the distance between the hydrophone and the transducer of $z = 270$ mm. Figure 5.2 shows a plot of hydrophone signal against its position at the far field boundary.

Figure 5.1 The spatial acoustic pressure pattern by hydrophone scanning of a 1 MHz, 40 mm diameter non-focused transducer, $z = 10$ mm (near field).

Figure 5.2 The spatial acoustic pressure pattern at a distance of $z = 270$ mm from the transducer face (far field). The dashed line is the theoretical expectation (*square root of Airy Pattern* for $D=32.1$ mm). The theoretical expectation has been normalized at the peak.

5.2 Comparison between Sidelobes of Lens I, II and III

In this study the field patterns of simple lenses were measured at different distances between hydrophone and transducer in the beam direction (z axis). The procedure of these experiments was similar to that of section 5.1 except for the lens alignment procedure described in section 4.4.4 while the distance between the transducer and lens kept at 10 mm in all lens studies.

A feature of a converging lenses is that its greater thickness towards the edge reduces the edge activity of the beam, which results in a reduction in the side lobe pressure or intensity and the beam profile approaches a Gaussian shape which is sometimes advantageous.

Figures 5.3, 5.4 and 5.5 show the hydrophone signal (mV) against position (mm) for lens I, II and III respectively. Lens I, II and III have 10 mm, 14 mm and 26.7 mm thickness at their edge respectively. The Radii of curvature and diameters were as in section 4.3.

Figure 5.3 The spatial acoustic pressure of lens 1 of 10 mm thickness at the rim.

Figure 5.4 The spatial acoustic pressure pattern of lens II of 14 mm thickness at the rim.

Figure 5.5 The spatial acoustic pressure pattern of lens III of 26.7 mm thickness at the rim.

5.3 Field Plots of Lens III

The measuring procedure described in section 5.2 was repeated. Lens III had a radius of curvature of 46.75 mm and the standard 60 mm diameter and rim thickness 26.7 mm. A plot of acoustic pressure vs. transverse position (z axis) is shown in Figure 5.6. The best focus was found at about 100 mm from the lens. A series of plots of acoustic pressure with the hydrophone scans in transverse direction (x axis) is shown in Figure 5.7(a) to 5.7(h). Each graph from (a) to (h) corresponds to different distance (70 mm to 300 mm), of hydrophone from the lens. Table 5.1 shows the Full Width at Half Maximum (FWHM) at different hydrophone distances from lens III taken from these figures. One may see the best focus at about 100 mm (Figures 5.6, 5.7 and table 5.1) where the FWHM is at its minimum (4.8 mm).

Table 5.1 The measured half-power beamwidth (mm) at different hydrophone distance from lens III.

Distance From Lens (mm)	70	100	105	120	150	200	250	300
FWHM (mm)	6.8	4.8	5.0	5.1	6.0	14.6	18.7	33.7

Figure 5.6 Acoustic pressure vs. z distance for a simple plano-concave lens (III).

Figure 5.7 (a) The acoustic pressure scanned in transverse direction, x - axis, for a simple plano-concave lens (III); the distance between the hydrophone and the lens is $z = 70$ mm.

Figure 5.7(b) The acoustic pressure scanned in transverse direction, x -axis, for a simple plano-concave lens (III); the distance between the hydrophone and the lens is $z = 100$ mm. The dashed line is the theoretical expectation (*square root of Airy Pattern* for $D = 32.1$ mm). The theoretical expectation has been normalized at the peak.

Figure 5.7(c) The acoustic pressure scanned in transverse direction, x - axis, for a simple plano-concave lens (III); the distance between the hydrophone and the lens is $z = 105$ mm.

Figure 5.7(d) The acoustic pressure scanned in transverse direction, x - axis, for a simple plano-concave lens (III); the distance between the hydrophone and the lens is $z = 120$ mm.

Figure 5.7(e) The acoustic pressure scanned in transverse direction, x - axis, for a simple plano-concave lens (III); the distance between the hydrophone and the lens is $z = 150$ mm.

Figure 5.7(f) The acoustic pressure scanned in transverse direction, x -axis, for a simple plano-concave lens (III); the distance between the hydrophone and the lens is $z = 200$ mm.

Figure 5.7(g) The acoustic pressure scanned in transverse direction, x - axis, for a simple plano-concave lens (III); the distance between the hydrophone and the lens is $z = 250$ mm.

Figure 5.7(h) The acoustic pressure scanned in transverse direction, x -axis, for a simple plano-concave lens (III); the distance between the hydrophone and the lens is $z = 300$ mm.

5.4 Field Plots of Zone Lens

The zoned lens had the same diameter and design focal length as the simple lens. It had three zones with step heights of 3.22 mm between the zones, and the areas of three zones were equal. It was expected that in this way the amplitude contributions from each zone to the final focal region would be approximately equal and in phase. Since the zone lens was cut for making two steps, its thickness at the rim was about 20.9 mm. Therefore one expected a small increase in sidelobes compared with lens III in section 5.3.

A plot of acoustic pressure vs. distance, z axis, is shown in figure 5.8. The best focus was found at about 105 mm from the lens. A series of acoustic pressure plots for transverse scans (x -axis) is shown in Figures 5.9(a) to 5.9(i). Each graph from (a) to (i) corresponds to different distance (60 mm to 300 mm) of hydrophone from the lens. Table 5.2 shows the Full Width at Half Maximum (FWHM) at different hydrophone distance from the lens. One may see the best focus is about 105 mm (Figures 5.8, 5.9(a) to 5.9(i), and table 5.2) where the FWHM is at its minimum (5.0 mm).

Table 5.2 The measured half-power beamwidth (mm) at different hydrophone distance from zone lens.

Distance from Zone Lens (mm)	60	80	100	105	110	120	200	250	300
FWHM (mm)	8.3	6.0	5.1	5.0	5.2	5.8	18.3	22.1	42.4

5.5 Comparison Between Plots of FWHM for Simple and Zone Lenses

A plot of *FWHM* for simple lens on the basis of data from Table 5.1 and similarly a plot of *FWHM* for zone lens on the basis of data from Table 5.2 has been shown in Figure 5.10.

One may see that the zone lens has a smaller depth of focus in contrast to the simple lens, refer to the section 3.5 and Figure 3.6. The two plots are in good agreement with each other and with the theoretical expectation.

Figure 5.8 Acoustic pressure vs. z distance, for a zone plano-concave lens.

Figure 5.9(a) Acoustic pressure vs. transverse distance, x axis, for a zone plano-concave lens; the distance between the hydrophone and the zone lens is $z = 60$ mm.

Figure 5.9(b) Acoustic pressure vs. transverse distance, x axis, for a zone plano-concave lens; the distance between the hydrophone and the zone lens is $z = 80$ mm.

Figure 5.9(c) Acoustic pressure vs. transverse distance, x axis, for a zone plano-concave lens; the distance between the hydrophone and the zone lens is $z = 100$ mm.

Figure 5.9(d) Acoustic pressure vs. transverse distance, x axis, for a zone plano-concave lens; the distance between the hydrophone and the zone lens is $z = 105$ mm. The dashed line is the theoretical expectation (*square root of Airy Pattern* for $D = 32.1$ mm). The theoretical expectation has been normalized to the peak.

Figure 5.9(e) Acoustic pressure vs. transverse distance, x axis, for a zone plano-concave lens; the distance between the hydrophone and the zone lens is $z = 110$ mm.

Figure 5.9(f) Acoustic pressure vs. transverse distance, x axis, for a zone plano-concave lens; the distance between the hydrophone and the zone lens is $z = 120$ mm

Figure 5.9(g) Acoustic pressure vs. transverse distance, x axis, for a zone plano-concave lens; the distance between the hydrophone and the zone lens is $z = 200$ mm.

Figure 5.9(h) Acoustic pressure vs. transverse distance, x axis, for a zone plano-concave lens; the distance between the hydrophone and the zone lens is $z = 250$ mm.

Figure 5.9(i) Acoustic pressure vs. transverse distance, x axis, for a zone plano-concave lens; the distance between the hydrophone and the zone lens is $z = 300$ mm.

Figure 5.10 Comparison of Full Width of Half Maximum (FWHM) for the zone lens (□ □ □) and simple lens (* * *). From these, the *depths of focus* are derived following Figure 3.6 : 49 mm for the zone Lens (A), 62 mm for the simple lens (B).

5.6 Comparison between Field Plots of Simple and Zone Lenses

A field plot for a simple lens in the beam direction, Figure 5.6, and field plot the of zone lens, Figure 5.8, have been replotted together in Figure 5.10. One may see that the two acoustic focal lengths and depth of focus are almost the same.

One may notice the small increase of pressure for the zone lens in comparison to the simple lens, Figures 5.10, 5.7 and 5.9. Due to reduction of thickness of zone lenses compared to the simple lenses one may expect that zone lenses have less attenuation and consequently less heating inside the lens body. However, in the present work, because the effective diameter of the transducer is not large enough to cover all zones, therefore, one should not expect that the two curves in Figure 5.10 to be different.

In field plots for the simple and zone lens one may notice a small increase of sidelobes for the zone lens, Figures 5.9(a) to 5.9(i), in contrast to the simple lens, Figures 5.7(a) to 5.7(h). This may be due to reduction of thickness of zone lens at the rim. The simple lens, as explained above, produces a wave front which tends toward a Gaussian profile. That is, the side lobes are suppressed and the minima are filled in. By contrast, the zoned lens, with its reduced absorption, tends toward an ideal lens, that is, with a wavefront of uniform amplitude. Hence, it gives a field plot

nearer the *Airy pattern*, narrower, with more pronounced side lobe features, as seen experimentally, Figures 5.7(b) and 5.9(d).

Figure 5.11 Comparison of acoustic pressure of the simple (***) and zone (+++) lenses.

5.7 Discussion

In ultrasound imaging, the resolution obtained with a lens, is defined as the *Full width at half maximum (FWHM)* intensity of the main lobe. Consequently, from equation (3.11) it is required that

$$H_c^2 = \left[\frac{2J_1(kax_1/ff)}{(kax_1/ff)} \right]^2 = 0.5 \quad (5.1)$$

where a is the radius of the lens and x_1 is the coordinate in the plane of observation, refer to Figure 2.7. If $kax_1/ff = 1.62$, then equation (5.1) will be satisfied. Thus, x_1 can be expressed in the form of

$$x_1 = \frac{1.62}{2\pi} \left(\frac{\lambda}{a} \right) f \quad (5.2)$$

or

$$FWHM = 2x_1 \approx 1.03 (f/D) \lambda$$

In this study $\lambda \approx 1.42 \text{ mm}$ and $D = 2a \approx 32.1 \text{ mm}$, so for focal plane which $f \approx 105.3 \text{ mm}$ it follows that the half-power beamwidth of the intensity pattern or *FWHM* is calculated from x_1 , and it is

$$FWHM = 2x_1 \approx 4.8 \text{ mm} \quad (5.3)$$

Since experimental curves, figures 5.7 and 5.9, were given in terms of pressure, and intensity is proportional to the pressure squared, then the measured *FWHM* is calculated at ≈ 0.707 maximum pressure.

Tables 5.1 and 5.2 tabulated *FWHM* of curves of figures 5.7 and 5.9. The measured *FWHM* of simple plano-concave lens, from table 5.1 for focal plane $f \approx 105.3 \text{ mm}$, is $\approx 4.8 \text{ mm} \pm 4\%$ which is in very good agreement with theoretical calculation, equation (5.3). The measured *FWHM* of zone plano-concave lens, from table 5.2 for focal distance $f \approx 105.3 \text{ mm}$ is $\approx 5.0 \text{ mm} \pm 4\%$ which is within $\pm 4\%$ of theoretical and measured value of simple lens.

Another parameter that one may compare between simple and zone lenses and calculated value is the size of focused spot. If $f \approx 105.3 \text{ mm}$, $\lambda \approx 1.43 \text{ mm}$ and $D = 2a \approx 32.1 \text{ mm}$ are substituted into equation (3.12) it will give $d \approx 11.5 \text{ mm}$. From figures 5.7c and 5.7d in focal region of simple lens, the measured value of size of focused spot is $\approx 12.1 \text{ mm} \pm 3\%$. Similarly from figures 5.9c and 5.9d in focal region of zone lens, the measured value of size of focused spot is $\approx 12.1 \text{ mm} \pm 3\%$ which is in good agreement with theoretical calculation, equation (3.12), within $\pm 5\%$.

In summary, it may be noted that the characteristics of simple and zone lenses are in good agreement with theoretical expectation with respect to *FWHM* and *size of focused spot*.

From Figure 5.10 we see that, utilizing the criterion of Christensen [18], Figure 3.6, that the *depths of focus* of the zoned lens are $49 \text{ mm} \pm 4\%$ and $62 \text{ mm} \pm 4\%$ for the simple lens; a decrease of $\approx 21 \%$.

CHAPTER 6

Conclusions

In this study, the method for the design of ultrasound zone plano-concave lenses has been discussed and their characteristics compared with those of the simple plano-concave lens. Experimental results demonstrate the validity of the method.

A hydrophone holder consisting of two rotational stages and one translational stage was designed to align the hydrophone along the acoustic axis of the transducer. Special precautions were taken to suppress spurious reflections from sides of water tank and around the hydrophone.

Throughout this study extensive care was taken in regard to the alignment of the transducer, lens and hydrophone. To align the lenses a method using a laser beam, section 4.4.4, was used. As well, in this study a computer program was used to process the data. The program includes calibrations, the data acquisition, and averaging.

Theoretical and practical aspects of focusing ultrasound with a solid plano-concave lens were presented. The propagation of ultrasound across interfaces, transducer, beam pattern and FWHM in focused and unfocused beam are presented. The above discussions were the basis of the comparison of the measured and calculated values of FWHM of simple and zone lenses.

For further studies while extensive care should be taken with alignment of transducer, lens and hydrophone. It will also be necessary to keep the temperature of the water constant during all measurements, because of the effect of temperature on the speed of ultrasound in both the lens material and the water and consequently, through the index of refraction, on the calculation of focal region and wavelength. It would be desirable also to repeat the experiments with transducers with larger effective area and possibly increasing the number of zones in the lens.

To summarize, an acoustic zone lens was made from plexiglass to produce a focus at a specific frequency, as a method of avoiding bulk heating. One would expect that zone lenses have less heating due to attenuation because the overall thickness of the zone lenses is less than the simple lenses, however, at the present work, the maximum pressure of the zone lens at the focus is as good as the simple lens. The

reason of this was partly that small aperture of our transducer did not fully cover all zones.

The features of geometrical acoustic lenses, simple and zone were reviewed and several simple and zone lenses designed. The performances of the lenses were discussed with respect to the half-power beamwidth or *FWHM*, and *size of focal spot*. By comparing the *FWHM* of simple and zone lenses, it may be noted that they are in agreement with each other and with the theory within $\pm 4\%$. The differences are also in agreement with theoretical expectation. From above discussion it is clear that the performance of simple and zone lenses is almost the same, while zone lens has less thickness. Therefore, the experimental results demonstrate the potential use of zone lens where high power is required, as in producing heated regions for hyperthermia or tissue destruction.

Appendix A

Computer Program

This program is developed for Datascan Data Acquisition System to do the following :

- 1- Scan hydrophone and record data on a disk file.*
- 2- Calibrate hydrophone signals and corresponding positions.*
- 3- Process the data.*
- 4- Produce hard copies.*

The program is written in *GW BASIC*, and was run on a 286-AT IBM compatible microcomputer.

```

10 DIM RES (2)
20 FILE$="A:DATA.TST":FILEIN$=FILE$:FILEOUT$=FILE$
30 DIM DT(2000,2)
100 SCREEN 0,0,0 : CLS
120 PRINT " WELCOME TO DATA ACQUISITION STATION"
130 LOCATE 4,9:PRINT "1 - scan and record data"
140 LOCATE 6,9:PRINT "2 - print data to printer"
150 LOCATE 8,9:PRINT "3 - retrieve stored data and manipulate"
160 LOCATE 10,9:PRINT "4 - graph stored data"
170 LOCATE 12,9:PRINT "5 - exit"
180 LOCATE 14,12:PRINT "YOUR CHOICE"

```

```

190 LOCATE 14,7:INPUT A%
200 '
210 IF A% = 1 THEN 1000
220 IF A% = 2 THEN 7000
230 IF A% = 3 THEN 5000
240 IF A% = 4 THEN 15000
250 IF A% = 5 THEN END
260 GOTO 100
1000 ' scan and record data
1009 '
1010 ' set up data scan
1011 '
1020 OPEN"com1:9600,n,8,1,rs,cs0,ds0,cd0" AS#1 LEN=10
1030 B$=CHR$(5)
1040 PRINT #1,B$
1050 GOSUB 4500
1060 PRINT#1,"ti":GOSUB 4500
1070 PRINT#1,"tc"
1080 PRINT#1,"ss"
1090 FOR I=1 TO 5000:NEXT
1100 PRINT#1,"ct1,2,2"
1110 PRINT#1,"cs1,2,0,1"
1120 PRINT#1,"rm1"
1130 PRINT#1,"sc1,2"
1140 GOSUB 4500
1142 '
1143 '
1150 CLS : PRINT "      SCAN AND RECORD DATA."
1155 T$=FILE$
1160 LOCATE 10,15:PRINT "NAME OF DATA FILE (";T$;:INPUT") ";FILE$
1170 IF FILE$="" THEN FILE$=T$
1182 LOCATE 12,15:INPUT "x coord channel ";CHX
1184 LOCATE 13,15:INPUT "y coord channel ";CHY
1186 LOCATE 15,15:INPUT "speed of scan ";SPEED
1190 '
1200 OPEN FILE$ FOR OUTPUT AS #2
1210 '
1220 I = 0: CLS:RECORD=FALSE
1230 PRINT #1,"r11,2"

```

```

1240 LOCATE 3,10:PRINT "scan ";I;
1250 IF (RECORD) THEN PRINT "   RECORDING on file ";FILE$
      ELSE PRINT "   active file ";FILE$;"   "
1260 FOR J=1 TO 2:INPUT#1,RES(J):NEXT
1270 PRINT:PRINT:PRINT "           x-axis = ";RES(CHX);"           ":PRINT"
      y-axis = ";RES(CHY);"           "
1279 '
1280 IF NOT (RECORD) THEN 1290
1285  WRITE #2,RES(CHX),RES(CHY)
1287  I = I + 1
1289 '
1290 FOR J=1 TO SPEED:NEXT
1300 A$=INKEY$:IF A$="" THEN 1230
1310 IF A$="s" OR A$="S" THEN 1360
1320 IF NOT (A$="R" OR A$="r") THEN 1330
1325  RECORD = NOT (RECORD): GOTO 1230
1330 A$=INKEY$: IF A$="" THEN 1330
1340 GOTO 1230
1359 '
1360 CLOSE #1
1370 WRITE #2,9999,9999
1380 CLOSE #2
1390 '
1400 LOCATE 10,10:PRINT "DATA is stored on ";FILE$;" with ";I;" points"
1450 PRINT:PRINT "   Enter 'A' for again 'M' for menu ";
1460 A$=INKEY$:IF A$="" THEN 1460
1470 IF A$="a" OR A$="A" THEN 1000
1480 IF A$="m" OR A$="M" THEN 100
1490 GOTO 1400
4500 'subroutine to read and discard responses
4510 WHILE EOF(1)=FALSE
4520 A$=INPUT$(1,#1)
4530 WEND
4540 RETURN
5000 '
5005 CLS : LOCATE 5,10:PRINT "RETRIVE and ALTER DATA"
5010 LOCATE 8,10 : PRINT "1 - LINEARIZE X AXIS"
5015 LOCATE 10,10 : PRINT "2 - SORT FILE"
5020 LOCATE 12,10 : PRINT "3 - CALIBRATE X and Y AXIS"

```

```

5025 LOCATE 14,10 : PRINT "4 - AVERAGE POINTS"
5035 LOCATE 16,10 : PRINT "5 - EXIT"
5040 LOCATE 18,13 : PRINT " CHOICE":LOCATE 18,10:INPUT A%
5050 IF A%=1 THEN 5100
5060 IF A%=2 THEN 5500
5070 IF A%=3 THEN 10000
5080 IF A%=4 THEN 10200
5085 IF A%=5 THEN 100
5090 GOTO 5005
5100 ' LINEARIZE X AXIS
5110 GOTO 6000
5120 ' SUBROUTINE TO FIND TWO FILE NAMES AND SET UP FILES
5130 PRINT "          File name of INPUT data (":FILEIN$:") "':INPUT T$
5140 IF T$<>" " THEN FILEIN$=T$
5150 PRINT : PRINT "          File name of OUTPUT data (":FILEOUT$:") "':INPUT
T$
5160 IF T$<>" " THEN FILEOUT$=T$
5165 CLOSE #2:CLOSE #3
5170 OPEN FILEIN$ FOR INPUT AS #2
5180 OPEN FILEOUT$ FOR OUTPUT AS #3
5190 RETURN
5192 '
5200 '
5202 ' subroutine to read data points into array
5204 '
5220 '
5230 '
5240 '
5250 DTPT=0
5260 INPUT #2,X,Y
5270 WHILE ((X<>9999) AND (DTPT<1001))
5280   DT(DTPT,0)=X : DT(DTPT,1)=Y
5290   INPUT#2,X,Y : DTPT=DTPT+1
5300 WEND
5310 CLOSE #2 :RETURN
5320 '
5500 '
5502 ' sort data file
5504 '

```

```

5510 CLS : LOCATE 5,10:PRINT "SORT DATA FILE"
5520 LOCATE 10,1 : GOSUB 5120
5530 LOCATE 15,10 : PRINT "OK ... SORTING DATA ON PASS "
5540 GOSUB 5200
5545 LOCATE 17,30 : PRINT "total of ";DTPT;" data points"
5550 '
5560 SORTED = 1 : PASS = 0 : BOTTOM = 0
5580 WHILE SORTED=1
5590   SORTED = 0
5600   FOR I = 0 TO (DTPT- 1 - PASS)
5610     IF DT(I,0)>=DT(I+1,0) THEN 5650
5620       SORTED = 1:X=DT(I,0):Y=DT(I,1):DT(I,0)=DT(I+1,0):DT(I,1)=
DT(I+1,1):DT(I+1,0)= X:DT(I+1,1)=Y
5650   NEXT I
5660   LOCATE 15,39:PRINT PASS: PASS=PASS+1
5670 WEND
5675 '
5680 CLS : LOCATE 10,10:PRINT "DATA IS SORTED - RECORDING ON DISK ..."
5700 FOR I = 0 TO DTPT
5710   PRINT #3,DT(I,0),DT(I,1)
5720 NEXT I
5730 PRINT #3,9999,9999
5740 CLOSE #2 : CLOSE #3
5750 LOCATE 20,10:PRINT "PRESS M TO MENU ..."
5760 A$=INKEY$ : IF A$="" THEN 5760
5770 GOTO 100
6000 CLS :LOCATE 5,10:PRINT "LINERAIZE X-AXIS"
6010 LOCATE 10,10 : GOSUB 5120 : ' read two files
6020 GOSUB 15400 : ' find max and min x and y
6030 XINCRMT = (XHI-XLOW)/TOTAL
6035 '
6040 XVAL = XLOW
6045 '
6050 GOSUB 5165 : 'close and reopen files for input and output
6060 INPUT#2,X,Y
6070 WHILE X <> 9999
6080   PRINT #3,VAL,Y
6090   XVAL= XVAL +XINCRMT
6100   INPUT #2,X,Y

```

```

6110 WEND
6115 PRINT #3,9999,9999
6120 CLOSE #2:CLOSE #3
6130 '
6140 LOCATE 10,20:PRINT"LINEARIZATION COMPLETE ... press M for menu"
6150 A$=INKEY$ : IF A$="" THEN 6150
6160 GOTO 100
7000 '
7001 ' print out data
7002 '
7010 CLS : LOCATE 10,10 : PRINT "PRINT DATA TO PRINTER"
7020 LOCATE 14,10
7030 PRINT "File name of INPUT data (";FILEIN$;") ";;INPUT T$
7040 IF T$<>" "THEN FILEIN$=T$
7045 CLOSE #2 : OPEN FILEIN$ FOR INPUT AS #2
7050 GOSUB 5200
7060 LPRINT "FILE ";FILEIN$,DTPT;" POINTS"
7065 LPRINT "X-AXIS","Y-AXIS","X-AXIS","Y-AXIS"
7067 INPUT "ENTER FORMAT OF X-AXIS (##.###) ";;XAXIS$
7068 INPUT "ENTER FORMAT OF Y-AXIS (###.##) ";;YAXIS$
7070 LPRINT : LPRINT : LOCATE 20,10 : PRINT "... PRINTING ";FILEIN$;" ..."
7075 HALF = DTPT/2
7077 XAXIS$=XAXIS$+" ";;YAXIS$=YAXIS$+" "
7080 FOR I = 0 TO HALF
7082 LPRINT USING XAXIS$;DT(I,0); LPRINT USING YAXIS$;DT(I,1),
7084 LPRINT USING XAXIS$;DT (I+HALF+1,0); LPRINT USING YAXIS$;
DT(I+HALF+1,1)
7086 NEXT I
7090 LOCATE 20,10 : PRINT "FINISHED ... press M for the menu "
7100 A$=INKEY$ : IF A$="" THEN 7100
7110 GOTO 100
10000 ' CALIBRATE X
10010 CLS :LOCATE 5,10 : PRINT "CALIBRATE X AXIS"
10020 LOCATE 10,1 : GOSUB 5120
10030 CLS : LOCATE 5,10 : PRINT "CALIBRATE X AXIS"
10040 GOSUB 10500 : 'enter formula
10050 INPUT #2,X,Y
10060 WHILE X<> 9999
10070 NEWX=SLOPEX * X + INTX : NEWY=SLOPEY * Y + INTY

```

```

10080 PRINT #3,NEWX,NEWY
10090 INPUT #2,X,Y
10100 WEND
10102 PRINT #3,9999,9999
10105 CLOSE #2 : CLOSE #3
10110 PRINT : PRINT "all done press M for menu ..."
10120 A$=INKEY$ : IF A$="" THEN 10120
10130 GOTO 100
10200 '
10201 '
10210 CLS : LOCATE 5,10 : PRINT "AVERAGE POINTS"
10220 LOCATE 8,1 : GOSUB 5120
10230 LOCATE 14,10:INPUT "HOW MANY POINTS DO YOU WANT TO AVERAGE?"
";WTH
10240 GOSUB 5250
10250 NUM = 0 : WTH = WTH -1
10260 AVEX= 0 : AVEY = 0
10270 FOR I = 0 TO WTH : AVEX = AVEX +DT(NUM +
1,0):AVEY=AVEY+DT(NUM +1,1):NEXT I
10280 AVEX=AVEX/(WTH+1):AVEY=AVEY/(WTH+1)
10290 IF (AVEX<> 0) THEN PRINT #3,AVEX,AVEY
10300 NUM = NUM + WTH
10310 IF NUM < (DTPT-WTH)THEN GOTO 10260
10320 PRINT #3,9999,9999
10330 CLOSE #3
10340 GOTO 5005
10500 '
10502 ' get the formulas
10504 '
10510 PRINT : PRINT "enter x-axis in form Y = slope * x + int"
10520 INPUT " Slope = ";SLOPEX
10530 INPUT " int = ";INTX
10540 PRINT : PRINT "enter y-axis in form Y = slope * x + int"
10550 INPUT " Slope = ";SLOPEY
10560 INPUT " int = ";INTY
10570 RETURN
15000 '
15010 CLS : LOCATE 10,10 : PRINT "GRAPH STORED DATA ..."
15015 FILE$=FILEOUT$

```

```

15020 PRINT "enter DATA FILE to plot (";FILE$;":INPUT") ";T$
15030 IF T$<>" " THEN FILE$=T$
15035 '
15040 OPEN FILE$ FOR INPUT AS #2
15045 '
15050 SCREEN 2: CLS
15055 '
15060 GOSUB 15400: ' read input file #2 for max and min x and y
15075 '
15160 CLOSE #2
15165 '
15170 YRANGE = ABS (YHI-YLOW)
15180 XRANGE = ABS (XHI-XLOW)
15185 '
15190 OPEN FILE$ FOR INPUT AS #2
15200 INPUT #2,X,Y
15210 '
15220 WHILE X<>9999
15225 X=X-XLOW:Y=Y-YLOW
15230 LINE (ABS (620*(X/XRANGE)),190)-(ABS (620*(X/XRANGE)), ABS
(190-(190*(Y/YRANGE))))
15240 INPUT #2,X,Y
15250 A$=INKEY$:IF A$<>" " THEN GOTO 15280
15260 WEND
15265 CLOSE #2
15270 '
15280 LINE (0,190)-(639,190)
15290 LINE (0,0)-(0,190)
15300 LOCATE 1,10:PRINT "press 'm' for menu ..."
15310 A$=INKEY$:IF A$="" THEN 15310
15320 IF A$="m" THEN 100 ELSE 15310
15400 ' read data from file #2
15402 ' find hiest and lowest x and y
15404 '
15410 INPUT #2,X,Y
15420 XHI=X:XLOW=X:YHI=Y:YLOW=Y:TOTAL = 0
15430 '
15440 WHILE X<>9999
15445 TOTAL = TOTAL + 1

```



```
15450 IF X<XLOW THEN XLOW=X
15460 IF X>XHI THEN XHI=X
15470 IF Y<YLOW THEN YLOW=Y
15480 IF Y>YHI THEN YHI=Y
15490 INPUT#2,X,Y
15500 WEND
15510 '
15520 RETURN
```

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