the part of a student, plus an ability to understand and integrate knowledge dependent on other fields of study. Because of this, the faculty may hold the view that undergraduate students must be well-founded first in a basic science and, secondly, educated in the complex problems associated with marine studies at the graduate level. The introduction of marine subjects into an undergraduate program is viewed only as a mechanism for diluting the education in a basic science. This is a philosophical viewpoint that may not be warranted in all cases and is a function of the particular curriculum of both the graduate and undergraduate programs involved.

This author believes it is a general condition in marine sciences education that, outside of service-type introductory survey courses, the instruction in marine science starts with the same basic approach to the same subject matter and often from the same texts if taught at either the graduate or undergraduate level. There may be a difference in the depth of subject coverage between undergraduate and graduate programs. However, this difference probably is no more significant than differences between the same graduate (or undergraduate) course taught at different institutions or by different instructors at the same institution.

If this condition exists, then there can be considerable overlap between the course work in undergraduate and graduate degree programs, especially at the master's degree level. This must be compensated for in these programs at institutions offering both B.S. and graduate degrees to keep students progressing academically if they enter graduate school. There is no need to make this provision in those programs which are graduate only. This creates a course work inconsistency that can have students with a marine B.S. degree from one institution having had nearly the equivalent in course work of a master's degree candidate from another institution and vice versa.

It is interesting to note that the greatest hue and cry about the nonacceptability of marine B.S. degree students comes from the faculty of those programs which teach marine subjects as graduate courses only. This author can understand the reluctance of an established graduate program in accepting students who must be specially treated and offered alternative programs to prevent them from repeating course material already mastered. However, to use the argument that B.S. students are not acceptable because of a weak background in basic sciences is tenuous at best, since many of these students, in obtaining their B.S. degree, may well have shown they have sufficient background to perform in marine science course work equivalent to graduate courses.

The students who become involved in this also suffer from the discrepancy and nonstandardization of curriculums. Those obtaining a B.A. or B.S. degree from some schools have a much weaker educational background than those graduating from other programs. Yet they hold similar degree titles. This elevates one degree and depresses the other. Those B.S. degree programs that encourage students to take five years of study which earn them about 230-250 quarter credit hours and often as not a double B.S. degree, one in a basic science, the other in marine science, are further handicapped. Not only is the significance of their degree lessened by similar degrees from other, weaker programs when it comes to job hunting or applying to graduate school, but they are not receiving credit for having completed a marine course work program that is nearly equivalent to a master's program at many graduate schools.

The problems created by the undergraduate and graduate programs at one school and graduate programs at others are not easy to rectify. Yet, to let them remain is both a disservice to the students as well as to the academic field of marine science. It would seem that enough time has elapsed for academic programs to reach some degree of stability so they can be evaluated and compared to establish a ranking system that can be used as a guide for granting credit where credit is due. This author would recommend that an interinstitution academic group rise to the challenge of bringing order and guidance to those programs of marine science and to establish rules for standardizing course work programs in this field.

I. INTRODUCTION

A narrow-aperture liquid-filled conical acoustic lens, whose acoustic design is discussed in an accompanying communication by Stimler [1], was constructed for test and evaluation. The lens could contain up to 64 individual hydrophone elements mounted in a circle, each receiving energy from a separate beam intended to be 6° wide in the horizontal plane and 60° wide in the vertical. This paper presents information on fluid selection, design and construction of the case, window, fairing, sound-absorbing lining, and the results of acoustic tests. With a SOAB sound-absorbing lining, the lens model worked well, giving horizontal beam-widths of 6° and vertical widths of 30°. There is still a problem of compatibility between the SOAB and the Freon TF lens fluid selected.

II. FLUID SELECTION

The selection of the lens fluid was one of the easier problems. It was based to a large extent on information from a 1969 report written by Leader et al. [2]. This report listed 148 different fluids, their acoustic impedance, sound velocities and densities at 0, 20, and 40°C, and their velocity-temperature coefficients. TRICLOROTRIFLUOROETHANE (DuPont trade name Freon TF) was selected, partly because

Fabrication and Test Results of a Conical Acoustic Lens

GLENN N. REID

Abstract—This paper treats the fabrication problems and test results of an acoustic lens built in accordance with the acoustic design presented in an accompanying paper. Specific areas covered include the selection of the internal fluid, the window, construction of the case, sound-absorbing lining, and acoustic test results. With a SOAB sound-absorbing lining, the lens model worked well, giving horizontal beam-widths of 6° and vertical widths of 30°. There is still a problem of compatibility between the SOAB and the Freon TF lens fluid selected.

Manuscript received August 3, 1977; revised January 25, 1978.

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its sound velocity of about 700 m/s gave a refractive index of approximately two, relative to sea water. This permitted the receiving element ring to be mounted directly above the window. The price was the other significant factor. Freon TF costs $8.70/gal ($2.25/l) while other fluids with similar properties cost as much as $430/gal ($111/l). This lens requires 36 gal (140 l) of fluid for one fill, so the fluid could easily account for a major portion of the total cost. Unfortunately, Freon TF also has some unfavorable properties. It is considered a somewhat hazardous material, and it has detrimental effects on many rubber compounds.

III. CASE DESIGN AND CONSTRUCTION

The nonwindow parts of the case were constructed from standard-size steel pipe with a 0.5-in (1.27-cm) wall and flat steel plate of the same thickness, cut, welded, and machined to the configurations shown in Fig. 1. All seals around the window and access ports were made with O-rings. The entire lens except for the window was coated on the outside with a closed cell neoprene foam to reflect sound. This combination kept sound coming directly through the case to the hydrophones about 40 dB below the desired focused signal through the window.

IV. WINDOW DESIGN AND CONSTRUCTION

The window is a truncated cone with sides 25° from vertical, 3.5 in (8.9 cm) high with two radial flanges top and bottom. (See Fig. 1.) When mounted in the case, the aperture is 1.5 in (3.81 cm) high. Windows so far have been constructed of acrylonitrile-butadiene-styrene (ABS) plastic sheet by vacuum forming. ABS was selected because of its low price and low acoustic losses. There were two problems encountered, however, with the ABS. The first was due to the thermal properties of the material which was vacuum formed over a male mandrel with the smaller diameter on top. As the ABS cooled, the flat material on top of the mandrel would shrink, causing the entire dish to rise off the mandrel. This problem was solved by cutting the unwanted center portion out of the dish as soon as it started to cool, but while it was still soft. The second problem with ABS and some other plastics is that they are subject to a phenomenon known as stress hardening [3] when used in certain solvents. The material can be soaked unstressed in the fluid with little effect, but if the material is stressed beyond a certain point while in contact with the solvent, it will become brittle within hours. This phenomenon has limited the useful life of the ABS windows to about one week so far. Future windows will probably be constructed from glass reinforced plastic (GRP) which will require a somewhat more expensive molding process.

V. SOUND-ABSORBING LINING

The first anechoic lining material used was type AA3 rubber tiles. These tiles were predicted to give 10 dB of absorption for normal incidence. Tests showed that they did not do this well at the low ambient pressures used for testing the lens. The tests also showed that levels of absorption closer to 20 dB were needed for adequate acoustic pattern ratios. SOAB, which is a butyl rubber heavily loaded with aluminum powder, was used quite successfully. Toulis [4] has described some early applications. The SOAB was purchased from B. F. Goodrich, and a lining was constructed utilizing wedges over a 1-in solid layer as shown in Fig. 2. The SOAB, however, would not have had a very long useful life if it were in contact with the Freon TF. To permit feasibility testing of the lens design, the SOAB was covered with a heavy layer of polysulfide rubber compound. This lining worked very well, giving 28-dB echo reduction for reflections off the far wall relative to the focused pulse, and greatly improved directionality patterns as shown in Fig. 3. The amount of echo reduction was determined by transmitting 0.1-ms pulses from a distant projector and detecting them with hydrophones in the lens. When the source is to the right in Fig. 2, hydrophone $H_1$ would detect the focused pulse, while $H_2$ would detect the pulse reflected off the far wall of the lens. Relative times of arrival were used to determine the travel paths for each arrival. Amplitudes of the focused and reflected pulses were compared as in the composite sketch of Fig. 4. Efforts are continuing to find a lining that is compatible with Freon TF without coating. B. F. Goodrich is now formulating SOAB type materials with different rubber compounds expected to be compatible with the lens fluid. Felt Metal Products of Brunswick Corporation is also investigating the use of felt metal as a sound-absorbing material.

VI. FOCUS TEST

To study the focusing phenomenon, the lens was equipped with a motor-driven mechanism to move the hydrophone in accordance with external commands to any point in a two-dimensional adjustment region shown as a dashed rectangle in
VII. TEMPERATURE COMPENSATION

The lens must be compensated for the substantial change in fluid volume as the ambient temperature changes with location and time over a range of 28-85°F. This requires a compensator capable of handling 432 in³ (7.1). A hydroformed bellows is used for this purpose. This bellows, formed from 0.006-in stainless steel by the Mini Flex Corporation in Van Nuys, CA, has a collapsed length of 0.5 in (2.7 cm), an extended length of 4.5 in (11.4 cm), and has a 13-in (33-cm) diameter. The expected life is 100,000 cycles. 3/16-in (0.48 sm) thick flat end plates are welded into each bellows end. A very small opening is used to connect the bellows reservoir to the lens to prevent acoustic energy from getting into the lens via the bellows which is mounted outside the lens on the top.

VIII. FAIRING

Future efforts include developing a fairing to minimize flow noise as the lens is moved through the water. While this fairing has not been designed, one interesting concept under study is a molded one-piece GRP dome which would include the case as well as the window. The case portion, of course, would be thicker than the window, and a reflective coating would be used everywhere except over the window.

IX. CONCLUSIONS

An experimental lens has been built and tested, and its feasibility has been successfully demonstrated. Results as shown in Fig. 3 were excellent in terms of achieving the desired high front-to-back ratios and beam directivity, except for the fact that the vertical beamwidth is only 30° instead of the designed 60°. This phenomenon is not yet fully understood. The other major problem whose solution has not yet been demonstrated is the development of a sound-absorbing material compatible on a long-term basis with Freon TF. A highly effective sound-absorbing lining was the main key to success.
Opto-Acoustic Feasibility Design of a Conical Acoustic Lens

MORTON STIMLER

Abstract—The opto-acoustic design of a liquid-filled conical acoustic lens is discussed. An approximate model of stacked cylindrical elements is used to estimate the focal line. Final optimization is to be achieved experimentally. Diffraction enables point hydrophones to cover a vertical range of $60^\circ$. An iterative optimization procedure yields cone angle and window aperture size that give diffraction patterns to accomplish this with $3$-dB maximum loss at the extreme elevations. Baffles are positioned by a ray-tracing analysis to minimize internal acoustic reflections. Reflection losses <1 dB are predicted above the critical angle (for total internal reflection) at the water-window boundary.

I. INTRODUCTION

A. Purpose

The object of the work presented in this paper is to investigate the feasibility of a conically shaped acoustic lens for underwater acoustic research. The lens shape permits detection and localization of far field sound sources over the horizontal range of $360^\circ$, and from $+15$ to $-45^\circ$ of vertical range (horizontal taken as zero reference). This paper presents the theoretical considerations and approximations in an opto-acoustic approach used in the design of the first feasibility test model.

B. Background

One conventional method for acoustically detecting and localizing noise sources in the ocean is the use of hydrophone arrays. Individual hydrophones detect only that portion of the acoustic signal intercepted by their cross-sectional area. Beam forming equipment for a large array tends to be complex and cumbersome. In recent years, the idea of focusing larger cross-sectional areas of acoustic radiation in a lens has been investigated as a simple way to increase signal-to-noise ratios and to provide directivity. The opto-acoustic analog has been recognized [1], leading to the use of optical lens theory in the study of acoustic lenses. Furthermore, various media are now available in which the velocity of sound differs sufficiently from that in water, and with a sufficiently good acoustic impedance match to water, to permit their use in the design of practical underwater acoustic lenses [2]–[4]. One of the problems still existing is that the state-of-the-art in acoustic lenses is far less developed than in optical lenses. Commercial acoustic lens components are usually not available to solve specific acoustic lens problems. In addition, diffraction in the acoustic case will generally be large since the wavelengths of interest will often be on the same order of magnitude as the window aperture dimensions. This may be seen from the basic diffraction equation for normally incident radiation of wavelength $\lambda$ on a slit type aperture of width $b$ [5]

$$\sin \theta = \lambda/b$$

where $\theta$ is the angle from the center of the slit to the first minimum in the diffraction pattern. In our application, $\lambda \approx 2$ cm and $b \approx 4$ cm, giving diffraction angles on the order of $\theta = 30^\circ$. This effect, which is usually negligible in optics with apertures of such dimension, must be considered as an integral part of the lens behavior in the acoustic case. In fact, this feature is utilized in the present lens to allow fixed point hydrophones to cover the desired vertical range.

II. THEORETICAL

A. Lens Description

Fig. 1 is a vertical cross-sectional view showing the conceptual feasibility design of the planned acoustic lens. Acoustic energy enters the housing only through the conical acoustically transmitting window, shown at the bottom of the cylindrical housing. The case must therefore be made of material which is a good acoustic reflector, such as steel, or it must be coated with an acoustic reflector, as indicated in Fig. 1. The internal structure contains a ring of 64 hydrophone sensing elements for signal detection, and a system of baffles for suppressing internal reflections. These are immersed in an acoustic lens fluid Freon TF, a commercially available industrial solvent with an index of refraction in the desired range for focusing. This was chosen as the lens fluid for the first test model. The hydrophones are commercially available tubular ceramic units, $\frac{1}{2}$ in in diameter, and $\frac{1}{4}$ in long. An acoustic absorbing material covers the baffles as indicated. The acoustic window is made of a thin (~1.5 mm) material such as the plastic acrylic butadiene styrene (ABS). In calculations of focusing, refraction, and diffraction, this window was treated as a thin acoustically transparent membrane separating the acoustic lens fluid and the surrounding medium. This is a reasonable simplification since the window should have a negligible effect on the total refraction. Furthermore, it can be shown that internal reflection at the water–window boundary is "frustrated" [6] by the use of a window whose thickness is a small fraction of the acoustic wavelength. For example, in ABS at 40 kHz ($\lambda \approx 5.6$ cm), the loss due to reflection above the critical angle is calculated to be less than 1 dB [1], [6].

For the purpose of preliminary calculations, spherical aberration was neglected, and the conical lens was treated as a

REFERENCES


Manuscript received August 3, 1977; revised January 25, 1978. This work was funded by NAVSEa under Code 0342.

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