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AN ACOUSTIC LUNEBERG LENS FOR LOW-FREQUENCY SONAR USE

[UNCLASSIFIED TITLE]

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ABSTRACT
[Unclassified]

A brief description of the theory and operation of a Luneberg lens is made based on previous work of W. J. Toulis of the Navy Electronics Laboratory. Construction features are described which allow the fabrication of a lens for underwater acoustic use at low frequencies. The lens is a lightweight spherical array of flattened hollow tubing, properly spaced to control the compressibility (hence, index of refraction) throughout the lens. A model 5 feet in diameter to be girdled by a ring of omnidirectional hydrophones has been constructed at NRL for use with a proposed airborne sonar system. A number of beam patterns are shown. The directivity can be increased by using directional hydrophones. The tests reveal that reflections from the epoxy glue used in construction lowered the lens performance. There is a need for additional work with the Luneberg lens concept.

PROBLEM STATUS

This is a final report on one phase of the problem.

AUTHORIZATION

NRL Problem S05-11
Projects NA 443-002, and NR 443-000,
Task NR 443-008
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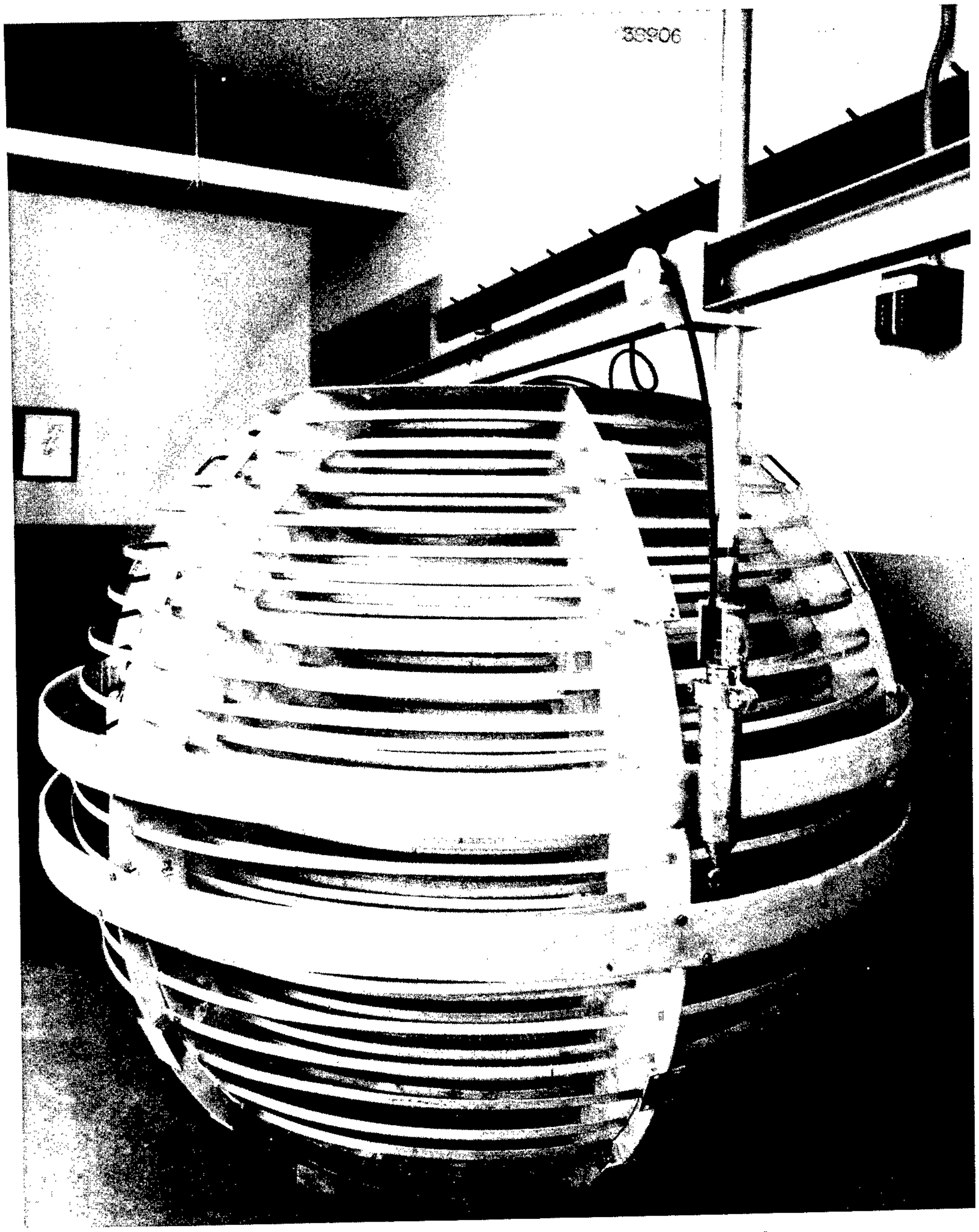

Acoustic Luneberg lens and one of the hydrophones to be attached to the Fiberglas bands

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AN ACOUSTIC LUNEBERG LENS FOR LOW-FREQUENCY SONAR USE
[Unclassified Title]

INTRODUCTION

Previous attempts have been made to focus sound waves with spherical lenses for sonar use, but they were restricted to small size and, consequently, high frequencies (> 20 kc). Usually they were thin-walled spheres filled with a fluid (e.g., CCl_4) having a sound velocity lower than that of water. This uniform index of refraction causes an inherent broad focal region because of spherical aberration. Temperature changes usually will deteriorate performance.

Luneberg (1) has shown by ray theory that point focusing can be obtained with a spherical lens having an index of refraction that varies with radius in a special manner. The theory of the Luneberg lens is relatively old, but the work to perfect one has only recently reached a stage where a practical model has been developed that could be used in the field of underwater acoustics. Such a lens has many attractive features for low-frequency sonar use in that it provides relatively narrow pre-formed beams in a manner much simpler than with conventional methods. The work reported on here is the result of an investigation of acoustic lenses for airborne sonar (lens and hydrophones to be dropped into the water from a helicopter or an airship). In the intended application, the acoustically pre-formed beams simplify the electronics and are well suited to optimum signal processing, while structually the lens can be made lightweight and has no critical dimensions or tolerances. A Low Frequency Active Sonar System, designated LOMASS-III, has been designed around the acoustic lens.*

THEORY AND OPERATION OF THE LENS

The following is a brief description of the theory and operation of the lens. For a complete explanation one should examine the reports on this subject (2,3) written by W.J. Toulis of the Navy Electronics Laboratory, who has perfected the above mentioned practical model.

A group of hydrophones is arranged in a circle about a sphere of special core material (see frontispiece). The output from each hydrophone is a beam associated with that hydrophone. Lens operation depends on the core material having an index of refraction μ (hence sound velocity) which varies with radius r as

$$\mu(r) = \sqrt{2 - (r/a)^2}$$

where a is the radius of the lens. This is the Luneberg equation for focusing to a point. As shown in Fig. 1, a sound ray entering the lens parallel to the axis is bent toward the axis by the action of the core and emerges from the opposite side at the axis. A bundle of sound rays having the diameter of the lens will be focused to a point on the opposite face of the lens. By placing a hydrophone at this point a gain is achieved, and for the main lobe a beam pattern is formed similar to that of a circular piston having the same diameter as the lens.

*A final NRL Report ([redacted]) on LOMASS systems is to be published

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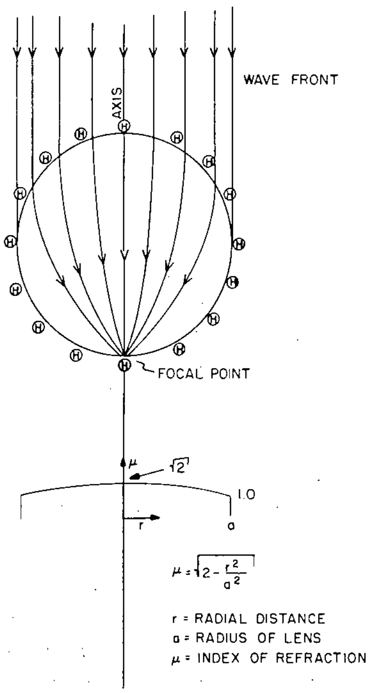


Fig. 1 - Ray diagram of the lens operation and the index-of-refraction profile of the lens

The index of refraction is varied by making the compressibility of the liquid a function of radius. Toulis's method of doing this is to form a spherically shaped array of relatively thin walled tubing that has been deformed to a flat ellipitical section leaving a small air gap inside the tube and the tube ends have been sealed. This flattened tubing, called compliant tubing, has a compressibility of constant value at low frequencies, a compressibility that is independent of depth at sea as long as the elastic limit of the material is not exceeded, and a resonance determined by its dimensions and mechanical properties.

The relation between tube spacing and compressibility is determined by making a planar array of tubes somewhat like a venetian blind and subjecting it to the action of plane sound waves. Tube orientation to the sound beam is not significant. It is found, for example, that a curtain of a given size and type of tubes with a center-to-center spacing of 3/4 in. has a resonant frequency (very large index of refraction) of about 12 kc, and below this frequency the index falls rapidly such that from 6 kc to 2 kc the index is almost constant, being 2.0 at 6 kc and 1.0 at 2 kc. A spacing of 1-3/4 in. gives an index of about 1.2 at 2 kc, and spacings between 3/4 in. and 1-3/4 in. give indexes between 1.2 and 1.0 at 2 kc. Because the index does not change rapidly with frequency, operation with compliant tubes is possible over a range of frequencies.

DEVELOPMENT OF THE NRL LENS

Since simple and lightweight structures are of paramount importance in directional airborne sonar systems, the lens lends itself readily to this application. Its ability to focus sound simultaneously from all directions without rotation is desirable from an operational standpoint; the ease and simplicity of beam formation compared to conventional methods is desirable from a sonar system point of view.

The Naval Research Laboratory has constructed and experimented with a lens to be used with an experimental helicopter-borne or airship-borne sonar system operating near 2 kc. An assessory projector is needed to complete the transducer system, since the lens cannot be used for transmitting, except for low intensities, without running into cavitation limitations at the individual hydrophones. In the helicopter application a line projector which will transmit omnidirectionally would be suspended below the lens, while on reception the hydrophone outputs would be scanned sequentially. Little or no loss is incurred on reception if the outputs are rectified and integrated before being scanned at a rate dependent on receiver bandwidth and the integration time constant.

CONSTRUCTION

The NRL model uses 3/8-in. aluminum tubing of two wall thicknesses, 0.022 and 0.028 in., to be formed into compliant tubes. When flattened the tubes are 5/8 in. wide with an air gap of about 0.025 in. An air gap wider or narrower (even a limited number of collapsed points) over small sections is allowed. Compliant rings are used instead of rods except at the center, where straight tubes are used because of the difficulty of making small rings. To obtain the desired index-of-refraction function the lens is built with a number of concentric shells. Each shell consists of compliant rings separated by a distance that gives the shell the required index at the shell radius according to the Luneberg equation (Table 1 and Fig. 2).

Consequently, this type of construction causes the index of refraction to vary in finite steps rather than continuously as required by the Luneberg equation. A step-by-step compromise is allowed, however, if the shell-to-shell or step distances are small compared with a wavelength and, arbitrarily, a step distance of $\lambda/10$ or 3 in. at 2 kc is chosen to give a sufficient number of refractive index increments to approximate a continuous variation. To attain a large lens diameter many steps are needed, and in the case described here 13 steps are used for a 60-in.-diameter lens.

Table 1
Ring Spacing for Each Shell

Radial Distance of Shell (in.)	Tube Spacing (in.)	Wall Thickness (in.)
1.98	1.98	0.022
3.96	1.98	0.022
5.98	2.02	0.022
8.00	2.05	0.022
10.0	2.10	0.022
12.1	2.16	0.022
14.3	2.25	0.022
16.5	2.37	0.022
18.9	2.54	0.022
21.4	2.82	0.022
23.8	2.04	0.028
25.8	2.48	0.028
28.8	3.00	0.028

Since the ray intensity falls off rapidly for rays near 90 degrees from the axis, the lens is cut down or truncated at the top and bottom to lower the vertical height to 50 in. Even with this reduction in size some 1400 feet of aluminum tubing is used.

Figure 3 shows the lens partially constructed with the straight center tubes mounted inside a free-flooding cylindrical tube of Fiberglas. The compliant rings are supported by six Fiberglas ribs cemented to the center Fiberglas tube. Each rib is made up of C-shaped segments, corresponding to the shell-to-shell separation, and the edges of each segment are notched to position the compliant tube rings. As each segment is cemented in position each of the rings is also glued to the segment to prevent the ring from mechanically vibrating against the rib. Figure 4 and the frontispiece show the completed lens with two Fiberglas bands for mounting the hydrophones. The lens is suspended by means of a circular plate attached to the center portion of the top member. Without hydrophones the lens weight is around 140 pounds, and with hydrophones the expected weight will be about 250 pounds.

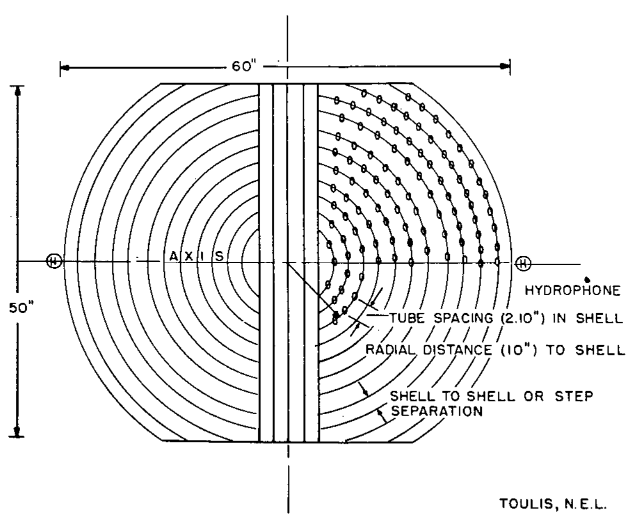


Fig. 2 - Cross-sectional view of the lens to show approximate tube location and shell structure

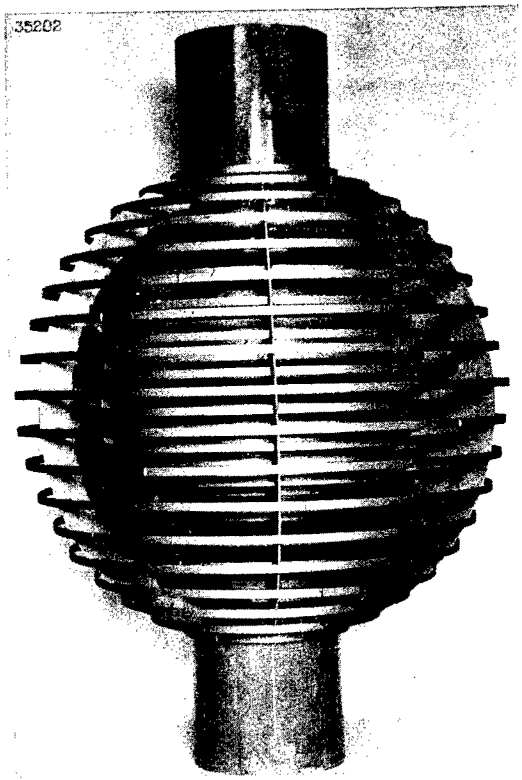


Fig. 3 - Lens partially constructed

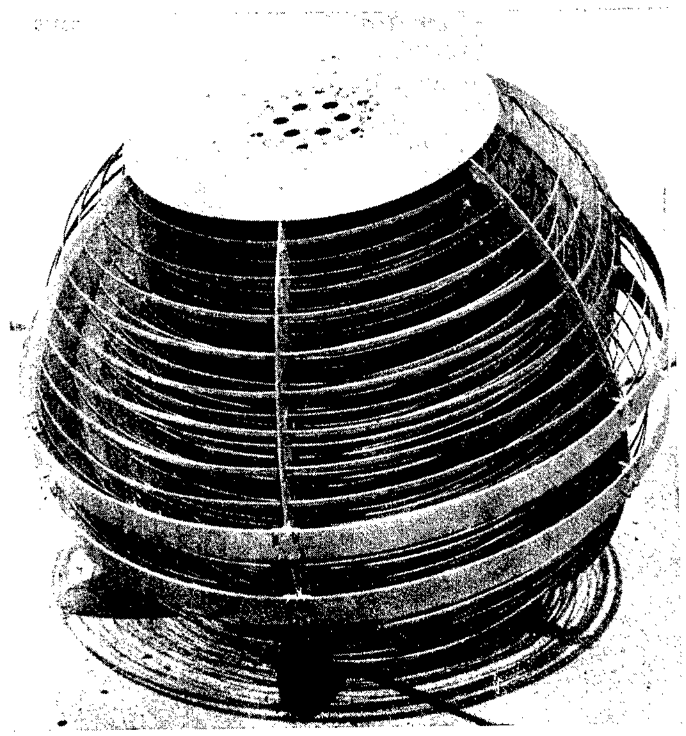


Fig. 4 - View of completed lens showing the circular support plate

RESULTS

Figures 5 through 8 are the lens beam pattern results over the usable frequency range for a simple omnidirectional hydrophone. Comment about the high back response will be made later. Comparison of these patterns with the pattern obtained from a circular piston would show the main beam similarity. Figure 9 shows lens gain and illustrates the broad frequency capabilities of the lens. In general, it can be said that this lens could be used for frequencies below 4 kc. But below about 1.8 kc the directivity is too low to be considered useful. Above 4.0 kc the lens gain drops sharply, because the compliant tube spacing becomes large with respect to the λ /10 criteria mentioned earlier. From these two limitations, then, the conclusion is made that the usable portion is from 1.8 kc to 4.0 kc.

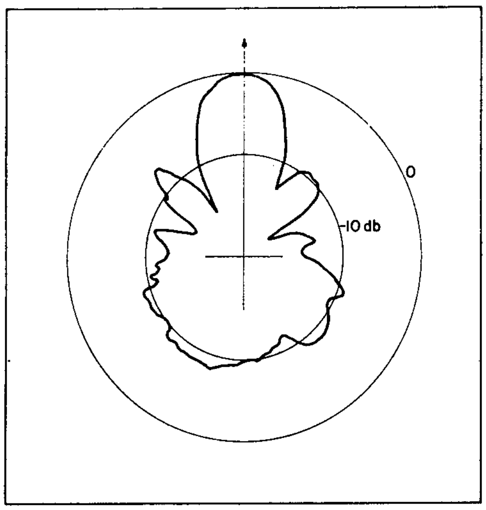


Fig. 5 - Lens beam pattern at 1.86 kc with omnidirectional hydrophone

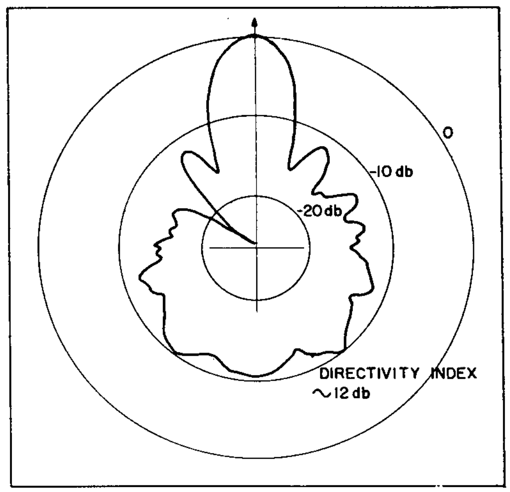


Fig. 6 - Lens beam pattern at 2.3 kc

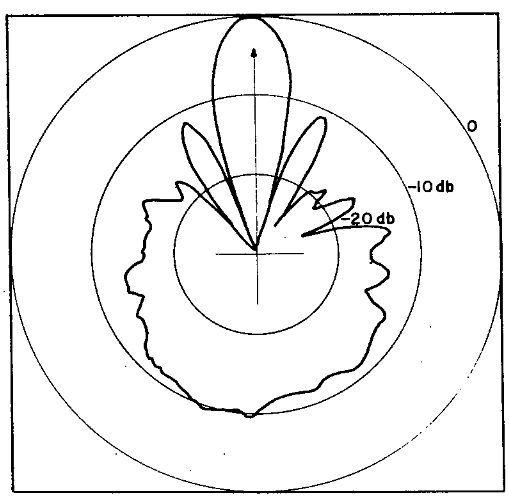


Fig. 7 - Lens beam pattern at 3.0 kc

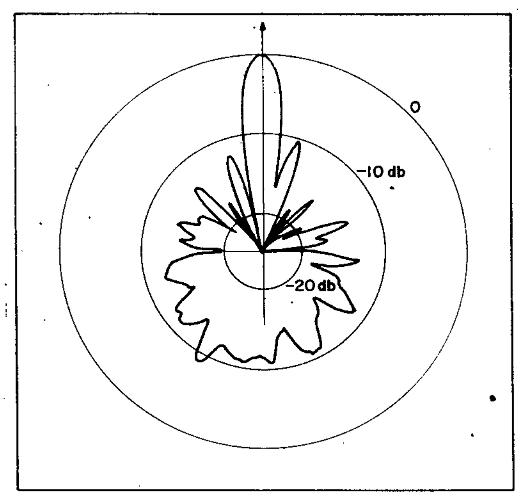


Fig. 8 - Lens beam pattern at 4.0 kc

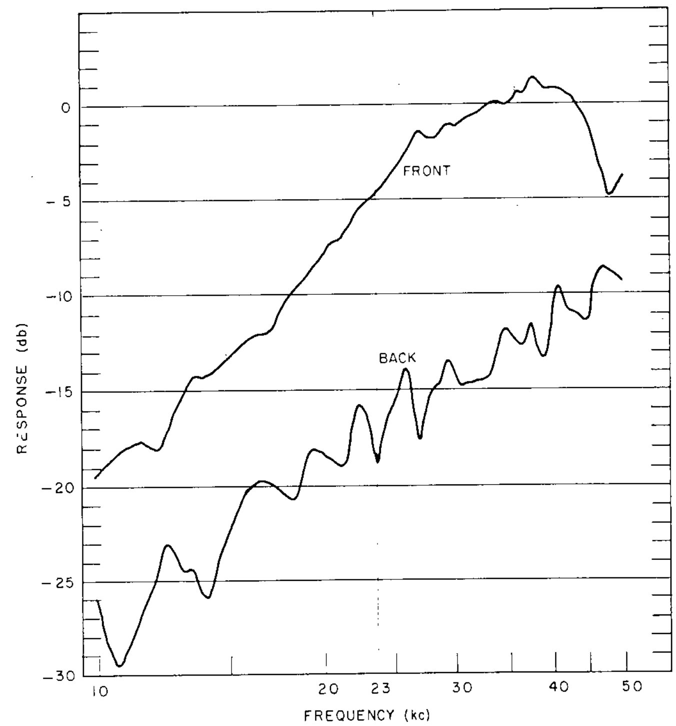


Fig. 9 - Lens front and back response to show the lens gain

Comparisons of Figs. 10 and 11 with Fig. 6 will show the degeneration that will occur if the Luneberg variation in the index of refraction is altered by objects which upset the controlled compressibility. Figures 10 and 11 are patterns which result when fish are present in between the compliant tubes. A fine mesh net, which did not trap air and thus change the compressibility, spread over the lens would prevent this from happening in field use.

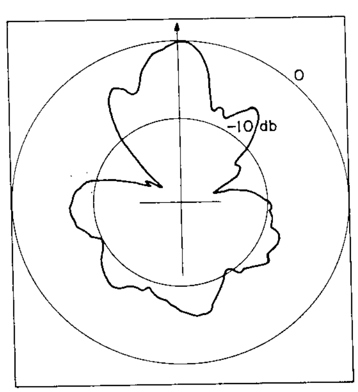


Fig. 10 - Lens beam pattern at 2.3 kc when there were fish in the lens

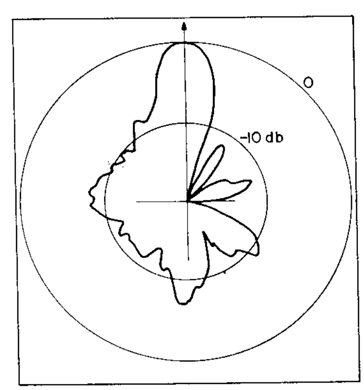


Fig. 11 - Lens beam pattern at 2.3 kc when there were fish in the lens

Mention was made of the high back response. The ratio of front response to back response for the lens, which is what is important, should be of the order of 16 db, whereas the results give only 11 or 12 db. Some experiments were performed to determine the reason for the loss. An interesting comparison can be made with Fig. 12 and the lower trace of Fig. 9. Both are plots of receiving response versus frequency, but the hydrophone of Fig. 12 is mounted midway between two of the Fiberglas ribs, while the hydrophone of Fig. 9 is mounted at the edge of one of the ribs. Nothing unusual is noticed with the edge-mounted result, but there is a noticeable pattern to the mid-mounted result of Fig. 12. This curve shows a cyclic variation in response that can be generalized as a periodic phase addition and cancellation effect due to reflections within the lens. Periodic cancellations occur at 2.2 kc, 2.7 kc, 3.3 kc, 3.9 kc, and 4.6 kc.

These results indicate that the rib structure acts as a corner reflector. Previous to lens construction, some tests were performed to determine the acoustic qualities of Fiberglas. No detrimental effects were noticed. So the reflections must be blamed on the too liberal use of epoxy cement used to fasten the lens member together. The deleterious effects of epoxy, due to trapped air pockets, are fast becoming known to transducer personnel. However, this was not known at the time of lens construction. Because of the method of construction, it would require total disassembly and complete reconstruction to remove the epoxy from the lens, and in the process some of the compliant rings would surely be damaged beyond repair.

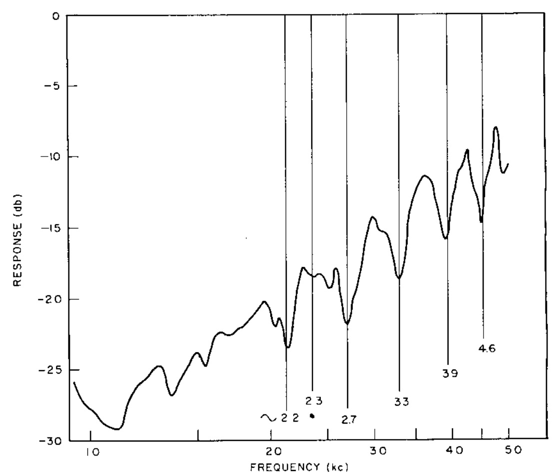


Fig. 12 - Back response with frequency when hydrophone is mounted midway between ribs

Some improvement in the front-to-back ratio can be obtained by using directional hydrophones. Methods of doing this plus their results with the lens are shown in Figs. 13 through 16. To get the result of Fig. 13 a 30 x 30 in. compliant tubing baffle or reflector is placed a quarter wavelength away from the hydrophone in order to increase the wanted response looking toward the lens as well as to decrease the unwanted response (back response of the hydrophone) looking away from the lens. This method has the serious fault of interfering with the hydrophones mounted on the other side of the lens, since it not only prevents sound rays from entering the lens but also disrupts normal lens focusing action.

The remaining three directional hydrophone results (Figs. 14a, 15a, and 16a) are obtained for arrays of omnidirectional hydrophones whose outputs are added in combinations, sometimes after a suitable phase shift. A drawing next to each resultant lens beam pattern illustrates the experimental configuration used along with a schematic representation of the phase shift performed and the manner of signal additional. Following each lens pattern is the pattern of the particular array used, to show the direction of the array by itself (Figs. 14b, 15b, and 16b).

The arrays used are by no means complete or the best choices available but merely serve to illustrate that the lens pattern can be improved by using simple directional hydrophones. However, a word of caution is in order in regard to some of the directional

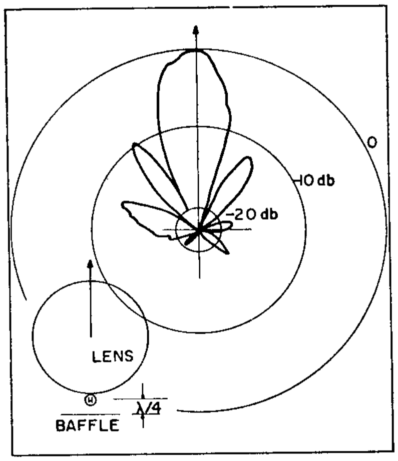
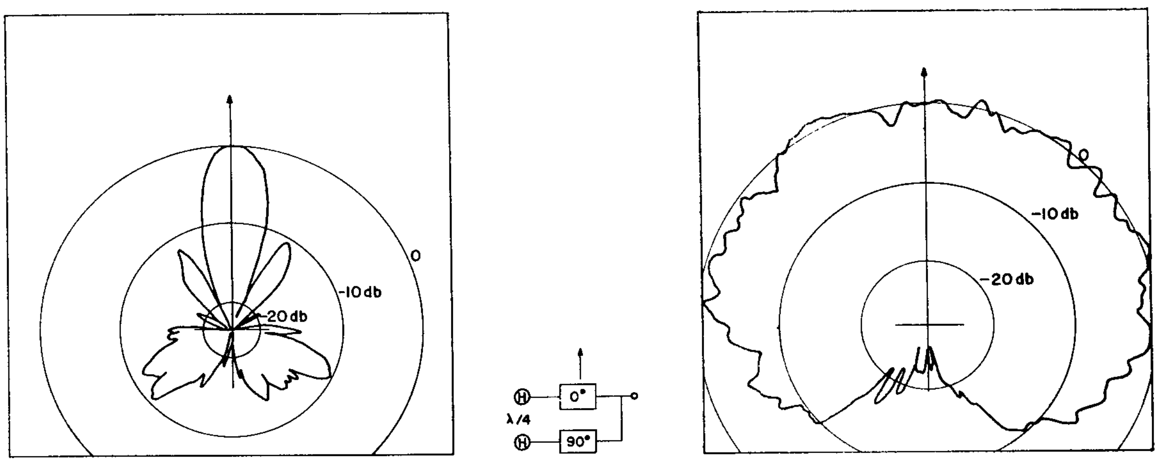


Fig. 13 - Lens beam pattern with omnidirectional hydrophone and 30 x 30 in. baffle



(a) With lens (b) Without lens

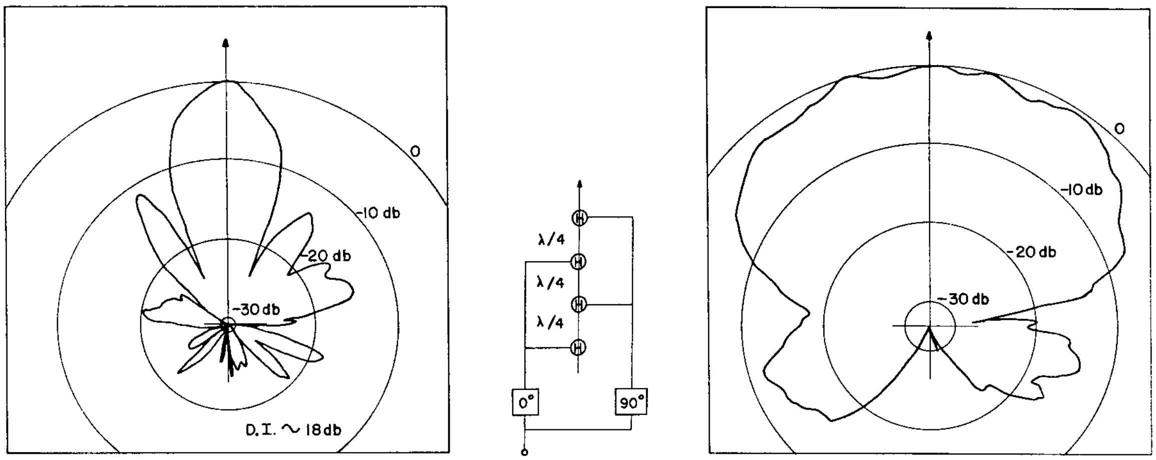
Fig. 14 - Beam pattern with a $\lambda/4$ doublet hydrophone array at 2.3 kc

arrays tried. In most cases they increase the overall diameter of the finished lens. The end-fire-array method requires four hydrophones per beam, which would result in a very large number of hydrophones for a lens having a sizable number of beams, and the resulting size and complexity may be too distracting.

All of the foregoing discussion has in mind beam formation for the normal sonar operation of detection. For information within the beam it is necessary to be able to obtain phase information. This phase information for high bearing resolution within the beam can be obtained from the lens by comparing the phase of two adjacent hydrophones. The position of the target is determined by this phase information. Figure 17 is a plot of experimental results showing phase difference with respect to mechanical rotation for three conditions of hydrophone separation. On this same figure is also shown the theoretical

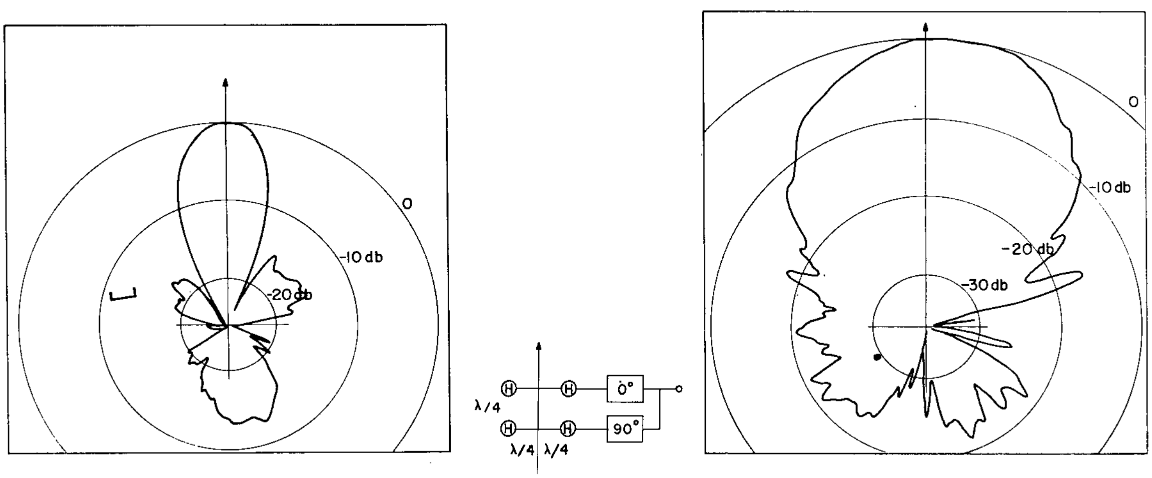
[redacted]

phase difference, under the 12-in.-separation condition, for the two hydrophones without the lens. The lens phase difference appears to be quite nonlinear, but in the usable portion (between the 3-db-down points) the error is small. Perhaps this could be corrected by modifications in the display.



(a) With lens (b) Without lens

Fig. 15 - Lens beam pattern with 4-hydrophone end-fire array at 2.3 kc



(a) With lens (b) Without lens

Fig. 16 - Lens beam pattern with 4-hydrophone array at 2.3 kc

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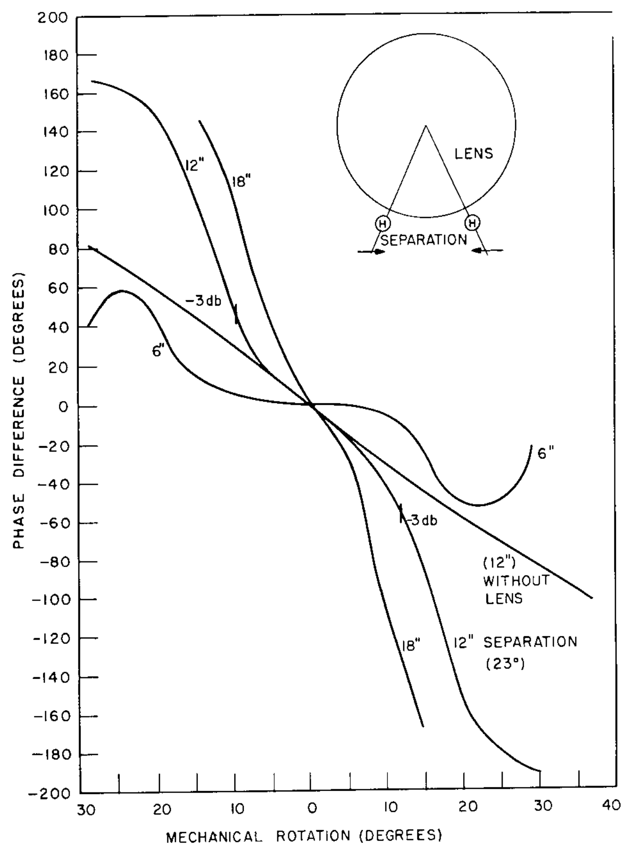

Fig. 17 - Phase relationship between two adjacent elements at 2.3 kc

CONCLUSIONS

As a simple and lightweight structure having the ability to focus sound simultaneously from all directions without mechanical rotation, the compliant-tube Luneberg lens shows great promise as a receiving transducer for a directional sonar system. Its ease and simplicity of beam formation, when compared to conventional methods, is impressive. Due to the nature of compliant tubes, lens operation is permitted over a range of frequencies.

FURTHER PROGRAM

To continue further tests with the lens it is necessary to construct a new one in such a manner that the troublesome reflections caused by the epoxy cement can be eliminated. It is considered too impractical to repair the present lens. One suggested method for improvement is to replace the Fiberglas with aluminum so that the ribs and compliant tubes can be fastened together, by welding or soldering, in such a fashion that the acoustic properties of the compliant tubes are preserved and at the same time the tubes are held in position with no interference from trapped air pockets in the structure.

Much work could be done to determine better directional hydrophone arrays to improve lens performance. Additional experiments should be performed to obtain improved bearing resolution beyond what has been outlined here. One item that has been barely touched upon is the handling capabilities of the lens. Little has been done toward determining the ability of the lens to withstand the sudden shock of being dropped into the water and dragged about or other types of rough handling that are typical of operating conditions. Such tests should await a more complete determination of acoustic performance. Improved lens performance can be obtained only through such development programs.

A program should be initiated to include the items mentioned above, if for no other reason than completeness, to finish a development that is only partially complete and one that shows much promise for improved sonar performance.

ACKNOWLEDGMENT

This work was facilitated through the assistance of W.J. Toulis, Navy Electronics Laboratory. His advise and services are appreciated.

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