the ACOUSTICAL LENS

By GEORGE L. AUGSPURGER

Operation and performance of various types of devices used professionally and in home hi-fi speaker systems to disperse and shape sound energy from horn-type driver units.

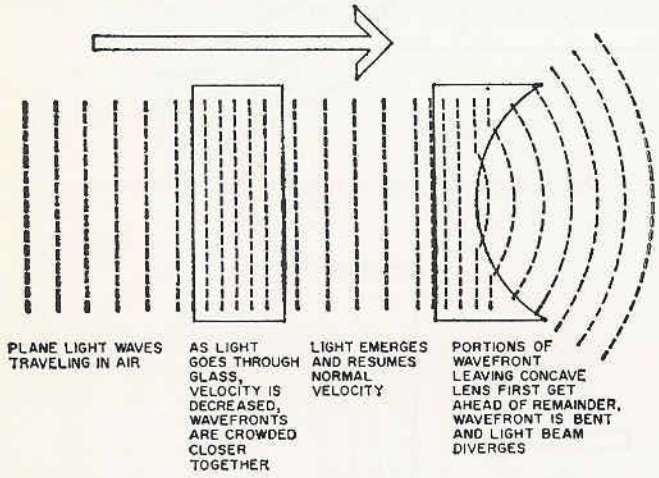


Fig. 1. Light waves passing through flat glass and concave lens.

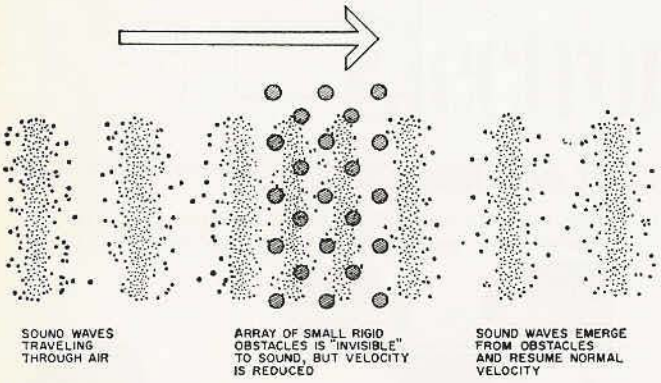
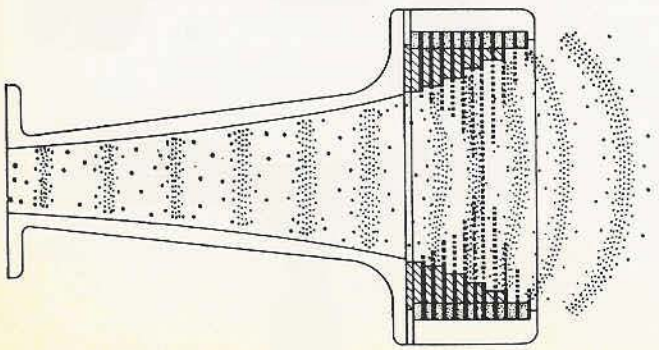


Fig. 2. Sound waves are shown passing through an obstacle array.

Fig. 3. Cross-section drawing of perforated-plate acoustical lens.



IN the last few years, more and more attention has been paid to the desirability of wide high-frequency dispersion in high-fidelity loudspeakers. This concern with a loudspeaker's distribution pattern is a good thing, but it is nothing new to the designers and users of professional equipment. In elaborate sound-reinforcement systems and theater sound installations, the problem is much more complicated than simply trying to avoid beaming of the treble frequencies. Careful control of loudspeaker directional characteristics is just as important here as are the optical properties of a spotlight to the lighting designer.

One of the most sophisticated, least understood, yet certainly most interesting methods of controlling sound directionality is the employment of an acoustical lens.

What the Lens Does

An acoustical lens is usually used in conjunction with a horn-type loudspeaker. The horn, especially in the high-frequency range, has numerous assets, but two major disadvantages: first, a good horn and driver combination tends to be more expensive than a cone-type loudspeaker and second, it is extremely directional. The first drawback is largely counterbalanced by the efficiency, dynamic range, and fidelity of the better units. The second can be overcome in a number of ways—by making the horn a special shape, by making a fan-shaped array of smaller horns, or by adding an acoustical lens. The lens introduces no tonal coloration and can be designed to give almost any desired directional pattern.

Historical Background

The possibility of making an acoustical lens, analogous in function and operation to an optical lens, first occurred to two *Bell Telephone Laboratories'* engineers who were working on refraction effects in conjunction with microwave transmission.

W. E. Kock and F. K. Harvey decided to see if certain techniques applicable to radio microwaves wouldn't also work, as theory suggested, with sound waves. In their experiments, they developed various acoustical converging and diverging lenses, as well as prisms.

The findings of Kock and Harvey were reported in the September, 1949 *Journal of the ASA* under the title "Refracting Sound Waves." The account is highly readable and remains the basis for present acoustical lens design.

How Acoustical Lenses Work

There are two basic classes of acoustical lenses: the "obstacle array" and the "path-length refractor." Both operate exactly as do optical lenses, by effectively slowing down a portion of the advancing wavefront as it passes through the lens.

When light passes through an optical lens, the effect is usually explained along the lines illustrated in Fig. 1. If we imagine a series of parallel light rays (as from the sun) this means that the wavefront is a plane surface. As this plane moves through, say, a piece of glass, it is slowed down momentarily. The refractive index, an omnipresent term in optics, is nothing more nor less than an indication of the relative velocity with which light travels through the medium in question.

So, our light wavefront slows down as it goes through the glass, then resumes its usual bustle when it gets back on the freeway. If the two surfaces of the glass are not parallel, but curved into the familiar lens shape, the part of the wavefront which has the least glass to go through resumes its normal velocity first and the wavefront is curved as it emerges.

Since the direction of travel of wave-propagated energy is at right angles to the wavefront, the light emerging from a lens tends either to diverge or converge, depending on whether the lens is concave or convex. Those who remember Huygens' principle will also probably recall the hours spent with ruler and compass laboriously plotting this effect.

To make the lens work with sound waves instead of light waves requires only that we find a substance which is transparent to sound, but which reduces the velocity of sound waves traveling through it.

The Obstacle Array

Harvey and Kock discovered that an array of small obstacles (small in comparison to any wavelength under consideration) has the same properties as a transparent homogeneous medium with a refractive index greater than one. In other words, sound will pass through such an array as if it wasn't there *except* that it comes out the other side just a little later than if it had traveled the same distance through air.

Fig. 2 shows what happens. The wavefront diffracts around individual particles, but in doing so its velocity is decreased. The obstacles, it was found, could be irregular, spherical, disc shaped, or parallel strips. Even a series of perforated plates exhibited the same refractive properties, and this configuration is obviously the easiest to use in constructing a concave, diverging lens.

Fig. 3 shows a cross-section of such a perforated-plate lens built into the mouth of an exponential horn. This basic design is used, for example, by *James B. Lansing Sound, Inc.* both in large theater assemblies and in smaller units for home high-fidelity installations.

Perforated-plate lenses are usually made of circular discs, and the resulting distribution pattern is symmetrical. The assembly shown at (B) in the photo, for example, has a smooth distribution pattern extending through a solid angle of about 90 degrees.

Path-Length Refractors

This configuration is easier to understand than the obstacle array since one can *see* why a portion of the wavefront is delayed. In this case, the delay is achieved by making a portion of the wavefront travel a greater distance to get from one side of the lens to the other. The enforced detour produces the same results as if the sound had traveled straight through at reduced velocity.

The two common varieties of path-length refractors are shown diagrammatically in Fig. 4. Sound traveling through the serpentine configuration winds back and forth until it emerges, while sound going through the slant-plate configuration travels in a straight line, *except* that the line is not its original direction of travel.

In the latter case, common sense tells us that the emerging wavefront will be heading in a different direction than when it entered. But common sense is wrong. Once through the detour, the sound continues in exactly the same direction as before! The separation between plates, remember, is small compared to a wavelength and the composite wavefront does not become tilted. If you are still suspicious, get out the ruler and compass and try Huygens' construction.

In terms of cross-section view then, a wavefront passing through either a serpentine or a slant-plate lens emerges traveling in its original direction, having only been slowed down momentarily. Where does the lens effect take place?

The answer is apparent if we look at a top view, as in Fig. 5. The design shown is equally applicable to either slant-plate or serpentine lenses, and it is easy to see that from this angle at least, the device has the characteristic of a diverging lens.

Such a path-length refractor can be compared to an astigmatic optical lens—it disperses sound waves in the horizontal plane while keeping them concentrated vertically. Such a distribution pattern is especially valuable in auditoriums and theaters where sound energy must be concentrated on the audience, and kept off reflecting surfaces to avoid excessive reverberation and echo.

Parts (A) and (C) of the photo show two *JBL* driver-horn-lens assemblies. The larger unit incorporates a slant-plate lens,

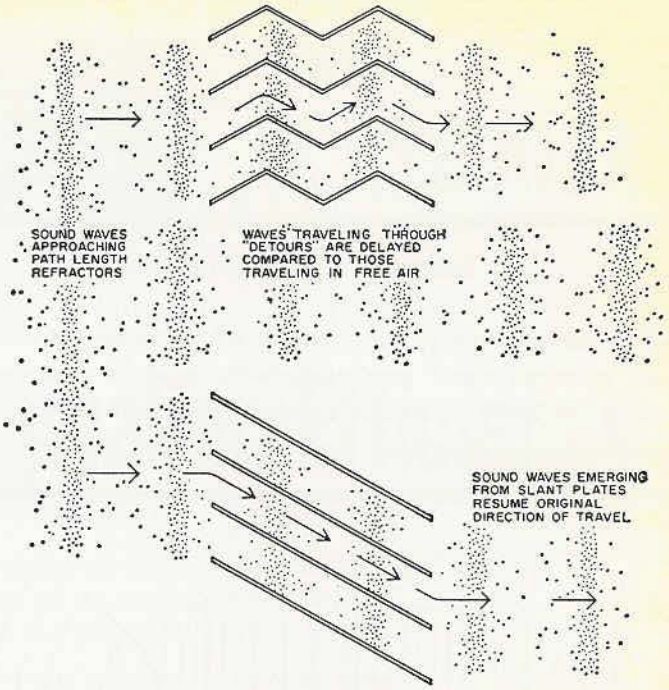


Fig. 4. Serpentine (top) and slant-plate path-length refractors.

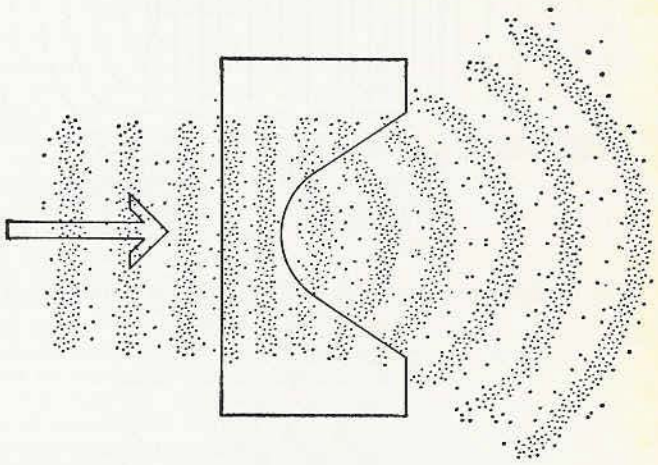
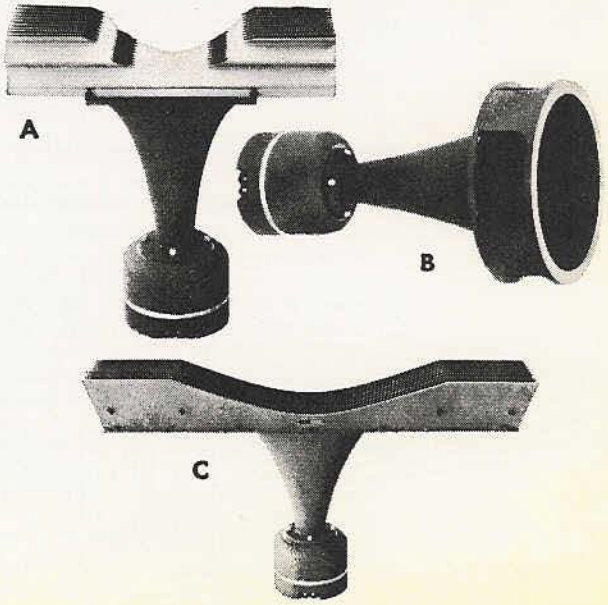


Fig. 5. Top view of slant-plate or serpentine acoustical lens.

High-frequency reproducers using (A) serpentine-type, (B) perforated-plate, and (C) slant-plate type acoustical lenses.



while the smaller has a serpentine lens.

Like the perforated-plate lens, path-length refractors can be designed to give almost any desired dispersion, but the ability to control horizontal and vertical distribution independently makes them even more versatile for professional use.

Design Considerations

Like optical lenses, acoustical lenses operate effectively only through a definite band of frequencies. The size of the horn mouth can be correlated with the characteristics of a particular lens to keep distribution uniform down to the cut-off frequency of the driver-horn combination. At the upper end of the spectrum, the smooth distribution pattern afforded by the lens begins to show irregularities as the spacing between obstacles or plates approaches a half wavelength.

This means that a lens designed for use up to 10 kc. should not have the plates separated more than a half-inch or so. Horn-lens combinations have been developed which maintain uniform dispersion characteristics from 400 to more than 15,000 cps. This is an effective bandwidth of about five octaves, obviously no mean achievement.

One might think that a substantial portion of the sound energy passing through a lens, especially an obstacle array, would be absorbed. As long as the lens is designed properly, and its elements are rigid, this is not the case. In a well-designed lens, less than 1% of the energy passing through the device is lost. Of course, in *any* type of dispersion arrangement, there is an apparent change in high-frequency intensity since all the energy which was formerly concentrated in a narrow beam is now spread through a much greater angle.

If one wants to pursue the optical analogy far enough, focal lengths and even *f* numbers can be assigned to acoustical lenses. The unit shown in part (B) of the photo, for example, is roughly equivalent to a 150 mm. *f*/0.5 optical lens. It will probably be some time before a comparable unit is available to camera enthusiasts. ▲

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