The Foley Acoustic Wave Front Slides

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In 1912 Arthur L. Foley of Indiana University published an article in Physical Review about his technique for photographing acoustic wave fronts. Subsequently, the Central Scientific Company published a series of glass lantern slides of his illustrations. These have been unavailable for about 60 years. Here I discuss how Foley made his slides and give examples of use to the present-day physics teacher.

Foley’s Technique

Wave fronts on the surface of water can be viewed directly, but acoustic wave fronts in air must use special techniques to render them visible. These depend on the idea that sound waves consist of compressions and rarefactions. The index of refraction of air depends on its density, with increasing density corresponding to a decrease in the speed of sound and a corresponding increase in the value of the index of refraction. Thus, a rarefaction is a region in which the index of refraction is slightly smaller than that of the surrounding air. In 1867 August Toepler (1836–1912), best known for his electrostatic machine that was a forerunner of the Wimshurst machine, used the Schlieren method that he devised to image wave fronts produced by electric sparks. This technique was extended by the American physicist Robert W. Wood (1868–1955) in 1900, but it required high-quality optics, either a lens without any variation in the density of its glass or a large aperture parabolic mirror.

The method suggested by Foley in 1905 and expanded upon in 1912 uses no image-forming optical parts. His technique can be seen in Fig. 1. The acoustic wave front is formed by a spark jumping between two short pieces of magnesium wire at location S in the middle of the long wooden box. The photographic plate is at location P at the right-hand side, and the spark that provides the illumination to form the image on the plate is at the left-hand side of the box at location I. The two ends of the box can be slid in and out to vary the object and image distances, typically about 1.3 m and 1.0 m. Foley used 8-x-10-in glass plates to record the images. The co-author was Wilmer H. Souder, who started to work on the problem of photographing acoustic wave fronts with Foley. The project was completed by Foley, working by himself.

The wave front is composed of a locus of points equidistant from S in which the air is expanded by the
spark. It has a decreased density and a smaller index of refraction. (It is assumed that the wave front expands rapidly, and so adiabatic conditions apply.) Light from the source spark is bent away from the wave front, which is imaged as a dark space on the photographic plate. An analogy is a ripple tank, in which the ripples form a series of converging and diverging lenses that form bright and dark images of the light source on the screen placed below the tank.

Figure 2 shows a cylindrical wave front emerging from the spark gap; the system is set up so that cylindrical waves, and not spherical ones, are produced. Other slides in this series show the wave front with smaller and larger radii, corresponding to earlier and later times. The timing is a matter of delaying the illumination spark by a certain number of microseconds; in Fig. 2 the time delay is 170 μs. The Leiden jar apparatus at the lower-left side of Fig. 1 accomplishes this; since this would be done using other techniques today, the delay method will not be discussed. This slide can be used to illustrate to students the fact that in a uniform medium, the disturbance spreads with the same speed in all directions. And, they can be reminded of isomorphisms: The same circular wave front is observed in ripples produced by drops in a pan of water and in the light reflected from dust in an exploding nebula.

The Slides

The rest of the slides show what happens when a circular wave front impinges on barriers of different shapes, and in some cases, different indices of refraction. The series appears in the 1929 Central Scientific Company catalogue at $19.50 for the set of 32 slides; individual slides were $0.60 each. The format was the 3¼-x-4-in glass-bound slide that was the standard for the time. For my own classes I made 35-mm transparencies from the original slides.

Figure 3 shows a circular sound wave being reflected from a plane surface 110 μs after it was emitted. The reflected wave is also circular and appears to be emitted from a virtual source on the left-hand side of the plane. This virtual source is, literally, a mirror image of the real source. Geometrical techniques can be used to locate the center of the reflected wave, and the mirror turns out to be equidistant from the real and the virtual sources. The dark ring indicating the rarified wave front has a lighter ring inside it, suggesting that a compression follows the rarefaction associated with the spark.

In Fig. 4 the source of the spherical waves is located at the focal point of a parabolic reflector. The reflected wave front is straight, showing that a parallel beam of sound is produced. The first picture shows the plane wave that is formed 110 μs after the creation of
The second picture, taken after a time delay of 190 μs, shows some distortion of the emerging plane wave front due to the residual heated air around the spark gap. The parabolic reflector has numerous uses in modern life: search lights, flashlights, optical and radio-frequency telescopes, and television dishes.

My favorite Foley slides are those showing the action of an elliptical reflector on a sound produced by a point source. The series of four slides in Fig. 5 shows how an acoustic disturbance at one focal point of the ellipse is focused, after reflection, on the second focal point. The total time is 300 μs, and this is the same for all reflected sound "rays." This can easily be connected to the construction of the ellipse using two pins and a pencil, which almost all students have seen. In my classes for non-science majors, this is used in conjunction with the study of theatrical spotlights with elliptical reflectors. Another link is to whispering galleries, in which the source of the faint sound is at one focal point of the ellipse and the ear of the listener is at the other.

Circular Huygens wavelets can be seen clearly in Fig. 6. Here, a circular sound wave impinges on a four-slit diffraction grating. Each opening in the grating is the source for a wavelet. The sound wave reached the center two slits first, and so the wavelets from these slits have larger radii than the ones from the two outer slits. Introductory students normally see diffraction gratings illuminated with parallel rays whose wave fronts are parallel to the slits. In the Foley illustration there is the interesting complication of the phase delay between the emitted wavelets. The backward-traveling wavelets that are ignored in the usual discussion of the Huygens method can be observed.

Two other series of slides show the effect of acoustic lenses on the circular wave front. In one case the lens is a thin, double-convex membrane filled with sulphur dioxide. Since the speed of sound in this medium is less than in air, the lens has an acoustic index of refraction greater than one, and the lens is positive or converging. Hydrogen has an index of refraction less than one, and so a hydrogen-filled double-convex lens has a negative focal length.

I have used the 35-mm copy slides of the Foley slide series since the early 1970s. The present-day teacher will probably blow up the illustrations from this article with a photocopying machine, and then make positive transparencies with the machine for use on the overhead projector. In either case, the slides can be used in a laboratory setting by projecting the images on to large sheets of paper and marking the reflecting surfaces and the wave fronts.

Foley’s sound wave front pictures were taken up by contemporary textbook authors. The earliest I have found is the second edition of Millikan and Gale’s textbook for high school students, published in 1913. The authors’ technique, as discussed in the preface, is to start with “some simple experiment or
some well-known phenomena.” The Foley slides are splendid examples of basic phenomena, and Millikan was quick to seize on them. The 1929 fourth edition of the physics textbook by Arthur L. Kimball of Amherst College, prepared by his son of the same name, shows the imaging by hydrogen and sulphur-dioxide lenses, and also Fig. 6 in the present paper.

Foley’s own text, published in 1933, has pictures of the reflection of spherical waves from parabolic and elliptical reflectors, and the focusing effect of converging and diverging mirrors. It also includes spark pictures of acoustic wave fronts reflecting inside a “well-known Chicago auditorium” that may have been made by the author.

**Arthur L. Foley**

Arthur Lee Foley was born in 1867, attended two small colleges in Illinois, and taught in the public
schools before graduating from Indiana University in 1890. His Ph.D. in physics was awarded by Cornell University in 1897. Meanwhile, he became a faculty member at Indiana, starting as an instructor in 1890 and becoming a professor and head of the physics department the year he received his doctorate. In addition to his work with the photography of wave fronts, he did research on surface tension, arc spectra, interference and diffraction, the velocity of sound, locomotive whistles, acoustic horns, microphones, and architectural acoustics. At one time he had a locomotive parked on campus as part of his program to improve train whistles. He also was a consulting engineer in acoustics for radio and phonograph manufacturers.

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