Reports

Multiplexing Ultrasonic Wave Fronts by Holography

Abstract. *Easily viewable, three-dimensional images have been produced from information derived from the passage of sound through the head of a living human subject. In this technique a new form of holographic multiplexing is used to construct the three-dimensional image from two-dimensional ultrasonic B-scans taken in many separated planes.*

The best-known optical representation of sound is the sound track on a motion-picture film. Such a track is not, however, a true picture of sound because it does not give any significant information about the spatial distribution of the sound field. When considering the recording of sound wave fronts, we are concerned with "picture-like" information, with sound waves rather than light waves as the information carriers. By "picture-like" information we mean that the points of the reconstructed optical image have the same spatial relation to each other as the actual points in the object. The result of acoustic imaging is called a "sonogram," and its basic ideas were developed in Europe in the late 1920's and 1930's.

In 1929, Sokolov (*1*) proposed a technique for the detection of flaws in metals in which the metals are transilluminated with an ultrasonic beam of several megahertz. Since liquid surfaces will deform as a result of sound pressure, Sokolov proposed to make the flaws visible by reflecting a collimated light beam from the liquid surface.

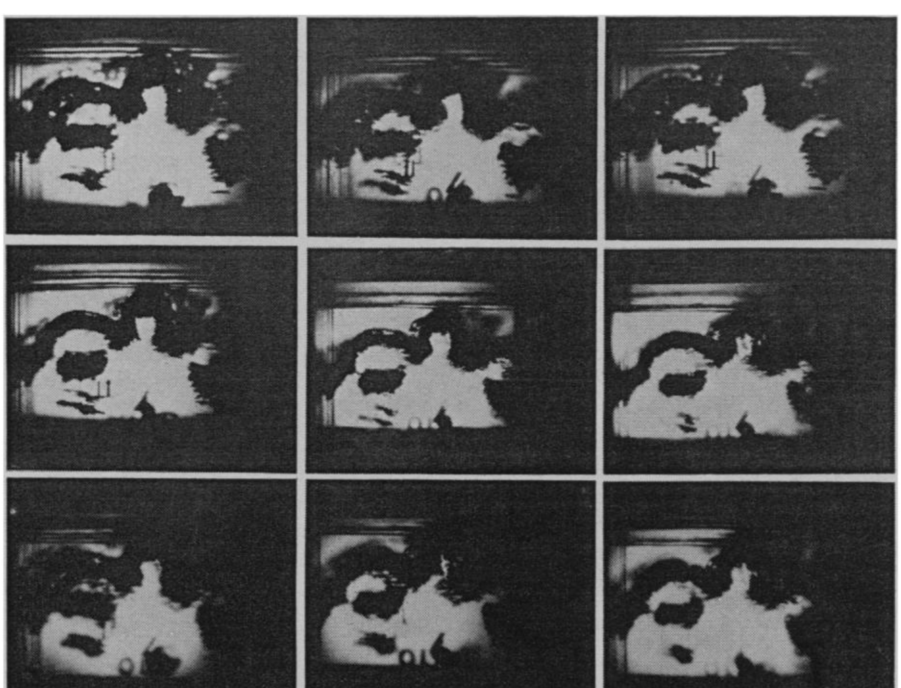

Fig. 1. Reconstructed picture of a space division–multiplexed ultrasonic quasi hologram showing different viewing angles of the head of a living subject and focused on different layers.

The direct imaging of acoustic waves, by analogy with the methods used in ordinary photography, also proved to be a useful technique. A variety of ultrasonic focusing elements were devised. The sonic image was recorded directly on a sonographic plate. The "exposure" of the sonographic plates depended on sonochemical reactions rather than on the photochemical reactions that are used in the development of photographic plates (*2*). Thus, the sound wave front was converted into a black-and-white image.

These black-and-white sonograms can be processed in such a way that we obtain a color image with different sound intensities corresponding to different colors. Although these colors do not correspond to spectral differences in the sound field, they do aid the viewer in acquiring information from the sonogram (*3*).

Both sonograms and photographs have severe limitations which arise from the fact that there is no way to utilize the phase information present in the wave front. In both cases, holography overcomes these limitations.

The development of optical holography was delayed by the lack of a highly coherent light source, that is, a laser. Highly coherent sound sources were available long before the laser but, surprisingly, ultrasonic holograms came into being after rather than before laser holograms. The first ultrasonic holograms were reported in 1965 (*4*). Since that time, considerable effort has been made to apply this technique to engineering, bioengineering, and medical problems. For example, Muller and Sheridon (*5*) and Brenden (*6*), like Sokolov, formed the ultrasonic hologram of a liquid surface. The ultrasonic imager of the Holotron Corporation is also based on this idea. The advantage of this system is that it allows a real-time display of the reconstructed image. Unfortunately, the disparity between the wavelengths of ultrasound and light leads to three-dimensional (3-D) images which are distorted in depth. Moreover, the problem of coherent speckle makes it important to display the 3-D images on a two-dimensional (2-D) device, for example, a cathode-ray tube. Thus, we see only 2-D "slices" of the object.

To overcome all the problems issuing from the wavelength discrepancies and to preserve the three-dimensionality of the reconstructed sonograms, we broke with the practice of adapting the laser hologram techniques to acoustic imaging. There is no need to transfer the spatial modulation due to the sound field directly into a light field, since this can be avoided by recording intermediate sonograms for subsequent 3-D display by means of optical holography.

In order to "see" an object in three dimensions with sound, we need a way to convert sound modulation to optical modulation and a way to display the optical signal in three dimensions. Sonic holography accomplishes both goals at once, but the resulting images are very difficult to view in three dimensions because of noise and distortion problems. We describe here a method of accomplishing the goals sequentially. First, we use ultrasonic B-scans to produce 2-D optical images of many "slices" through the object. Second, we use a new holographic multiplexing technique to "reassemble" a 3-D image by placing each 2-D image at its proper place in space.

A 3-D object can be considered to be built up from an infinite number of 2-D layers. The 3-D impression of the object is the result of the information on the relative positions of these layers (or "contours" of these layers). This position information is contained in the phase of the wave front and is evaluated automatically by our visual information-processing system. The wavelengths used in ultrasonic imaging are several orders of magnitude larger than those used in light imaging. The smallest distance between two planes that can readily be resolved in pulse-echo imaging may be expressed by

$$\delta = c\tau_P/2 \qquad (1)$$

where c is the velocity of sound and τ_P is the pulse duration. Thus, it is really not worth while to sample phase information on planes, that is, cross sections of the object, that are separated by a distance less than δ. This means, however, that, at the present stage of development of ultrasonic imaging, it is enough to have space relation information from cross sections about 10^{-2} cm apart, because the pulse duration is of the order of 10^{-7} second.

In ultrasonic nondestructive testing or diagnostics, pictures similar to a cross section of an object can be very easily obtained by the use of B-mode display or C-mode display techniques. Both the B- and C-mode displays are similar in appearance to x-ray pictures

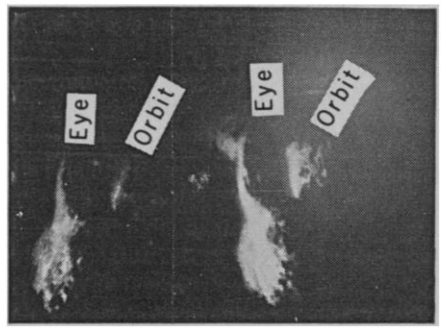

Fig. 2. Reconstructed image of the left temporal view of the same subject.

but with the following differences: (i) they represent real cross sections and not cross sections compressed in one plane as is the case with x-ray pictures; and (ii) in a B-mode display, the plane of the cross section is parallel to the direction of propagation of the probing wave front, whereas x-ray pictures and C-mode displays always represent a cross section perpendicular to the direction of propagation of the x-rays.

If several displays of this type could be assembled in a proper way in a single 3-D image volume, the resulting visual picture of the object would show the main features of a light wave-front reconstruction process, including its 3-D nature. One way to do this would be to exploit the possibility of wave-front multiplexing.

It is well known that on a single holographic recording medium many simultaneously reconstructible object wave fronts can be recorded. So, if a sequence of B-mode displays from different cross sections and viewpoints is taken and stored in an optical hologram, the reconstruction would yield a 3-D view of the structure. Since in this case the reconstruction consists of only the recorded displays and their relations to each other in space and not of the wave front of the information-bearing ultrasonic wave, there are no problems issuing from wavelength discrepancies.

This method also avoids one of the greatest problems associated with acoustical holography, namely, image speckle. Holograms of diffuse-scattering objects are characterized by "speckled" images. The speckle pattern is a result of a randomly varying phase across the face of the hologram. The light used in the reconstruction is modified by those variations in such a way that the image has a characteristic speckled (patchy) appearance (*6*). One way of making the speckles small enough to be unobjectionable is to record over a wide aperture. This solution, however, requires more information recorded on the hologram than present-day acoustical holograms can provide. By using optical holography, we can record over large enough apertures to make the speckle unnoticeable. Although this idea has already been proposed (*7*), its practical application was hindered by several factors, primarily by the fact that standard multiplexing techniques are not adequate for this application.

Basically two types of holographic multiplexing have been developed (*8*). In one type the holograms of each object are arranged side by side, each hologram occupying a small fraction of the photographic plate. This arrangement is not suitable for our purposes for many reasons. Perhaps the primary reason is that the viewer cannot see all of the images at one time. Rather he would have to switch in fast succession from image to image. This problem can be avoided if each hologram must share the whole photographic plate. This technique constitutes the second multiplexing method—multiple exposures over the whole plate. If, for example, we expose the whole holographic plate successively for each of N B-mode displays, the irradiance of any of the N wave fronts from the resulting holograms is of the order of $1/N^2$ of the irradiance that could be achieved by a single-exposure hologram (*9*). Thus a hologram of ten B-scans would produce ten images, each of which would be only 1/100 times as bright as the image that could have been produced by a hologram of only one B-scan. Both Greguss and Caulfield arrived independently, and practically at the same time, at the idea of sharing the full aperture among all the wave fronts by placing spatially complementary pseudo-random sampling masks immediately adjacent to the recording medium during recording; the reconstruction of the recorded wave fronts is performed without these masks (*10*). In this case, the degradation due to multiple exposure is avoided since every region is singly exposed.

In order to test these concepts, we recorded a hologram of nine cross sections of the head of a living subject. Each cross section was diffusely illuminated to facilitate viewing. The resulting image was fully 3-D as is suggested by Fig. 1. The surfaces which reflected the ultrasound are shown in black, and the areas from which there was no reflection are self-luminous. We are looking from the top of the subject's head and seeing (from left to right) the cross section of the right eye, the nose, and the left eye. The orbit of the right eye (black triangle) is normal. We infer this because, at the given setting of the equipment, ultrasonic energy is reflected from the whole orbit. The left orbit, however, has a tumor which absorbs a great deal of the ultrasonic energy and, therefore, we get reflections only from its boundary. If an observer focuses on different layers of the 3-D image and moves his head, he can see and even measure the 3-D position of the tumor. Figure 2 shows the left temporal view of the same subject, except that in this case the areas reflecting the ultrasound are self-luminous. If one cross section of the reconstructed scene is of particular interest, the perturbing effect of the other parts can be eliminated simply by placing the mask used to record that cross section back in place.

The primary drawback associated with this method is the time needed. Development of a fast scanning technique and various automated hologram recording techniques should ease this problem considerably.

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References and Notes

1. S. J. Sokolov, *Tech. Phys. U.S.S.R.* 2, 522 (1935).
2. P. Greguss, *Perspective (London)* 8, 287 (1966); H. Berger, in *Acoustical Holography*, A. F. Metherell *et al.*, Eds. (Plenum, New York, 1969), vol. 1, p. 27.
3. P. Greguss, *Res. Film* 7, 181 (1971).
4. ——, *ibid.* 5, 330 (1965).
5. R. K. Muller and N. K. Sheridon, *Appl. Phys. Lett.* 9, 328 (1966).
6. B. B. Brenden, in *Acoustical Holography*, A. F. Metherell *et al.*, Eds. (Plenum, New York, 1969), vol. 1, p. 57.
7. P. Greguss, in *Development in Holography*, B. J. Thompson and J. B. De Velis, Eds. (Society of Photo-Optical Instrumentation Engineers Press, Redondo Beach, Calif., 1971), p. 55; I. D. Redman, W. P. Woltan, I. E. Fleming, A. M. Hall, *Ultrasonics* 7, 26 (1969).
8. H. J. Caulfield and S. Lu, *The Applications of Holography* (Wiley, New York, 1970).
9. ——, J. L. Harris, *J. Opt. Soc. Amer.* 58, 1003 (1968).
10. H. J. Caulfield, *Appl. Opt.* 9, 1218 (1970); P. Greguss, report presented at the annual meeting of the Optical Society of America, Hollywood, Fla. (1970); Hungarian Patent No. 18606 (1970).
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Acceleration of Argon Ions to 1.17×10^{10} Electron Volts

Abstract. *Argon ions were accelerated to 1.17×10^{10} electron volts in the Princeton Particle Accelerator. The synchrotron was tuned by use of a neon beam with a charge-to-mass ratio equal to that of the argon ions. The fully accelerated argon ions were detected by the observation of etched tracks in cellulose nitrate sheets and also by the use of scintillation counters. Predictions of the range and of the characteristics of argon tracks in plastics were confirmed.*

Argon ions have been accelerated to 11.7 Gev in the Princeton Particle Accelerator (*1*). The acceleration to relativistic energies of a particle as massive as argon is of interest in the study of biological effects of heavily ionizing radiation, including applications in cancer therapy (*2*), in the study of radiation effects in space (*3*), and in astrophysical problems (*4*).

The argon beam was created by simultaneously accelerating argon and neon ions with nearly identical charge-to-mass ratios in the Princeton Particle Accelerator. The argon beam was too weak to yield a pickup electrode signal strong enough to permit tuning of the radio-frequency acceleration. The relatively intense mixed beam was used for tuning and adjusting the synchrotron—the separated argon beam was detected only at full energy after extraction from the accelerator. The ions were created as Ar^{4+} and Ne^{2+} in a Penning ion gauge (PIG) ion source in the high-voltage terminal of a 3.5-Mv Van de Graaff injector and subsequently stripped to Ar^{12+} and Ne^{6+} by a carbon foil (8 μg/cm^2). After simultaneous acceleration of both ions in the synchrotron to the final energy of 287 Mev/nucleon, the two beams were extracted and stripped to Ar^{18+} and Ne^{10+} (see Fig. 1A) and separated by a dipole magnetic field. The argon ions were identified by both tracks in plastic and scintillation detectors.

Stacks of sheets (250 μm thick) of

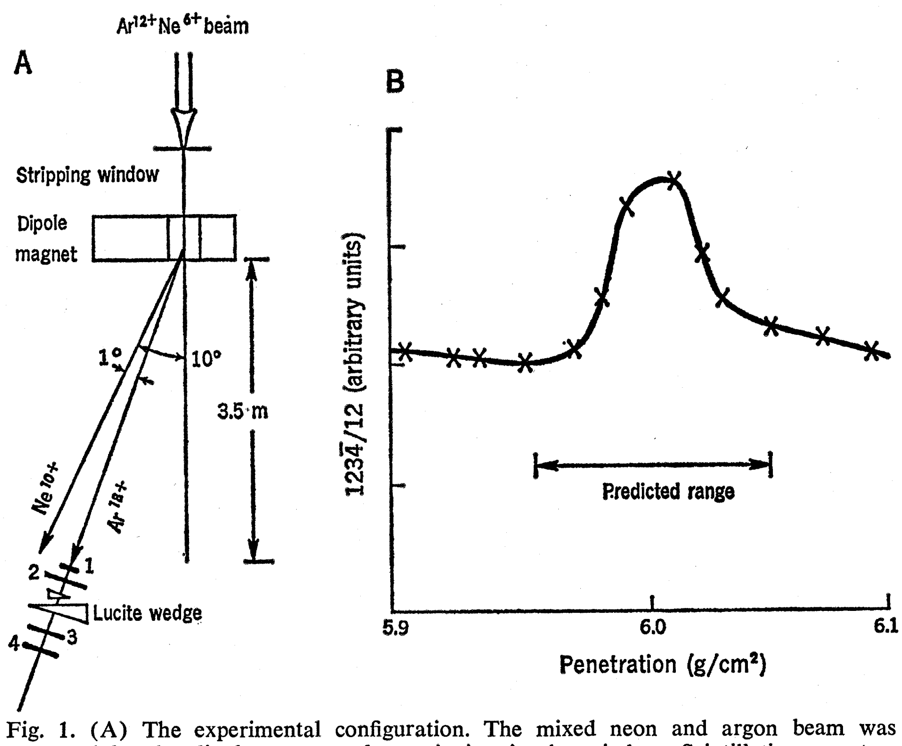

Fig. 1. (A) The experimental configuration. The mixed neon and argon beam was separated by the dipole magnet after stripping in the window. Scintillation counters 1, 2, 3, and 4 were used to detect the argon ions; the signal "$123\bar{4}$," which indicates the number of particles stopping in counter 3, was monitored as the Lucite wedge thickness was varied. This apparatus was also used for the cellulose nitrate exposure; the cellulose nitrate stack replaced counters 3 and 4. (B) The measured uncorrected signal "$123\bar{4}$"/"12" as a function of the total amount of absorber in the argon beam. A clean peak is seen at the predicted argon range. The uncertainty in the predicted range arises from uncertainties in the composition of materials in the beam. The precision of the variable Lucite absorber was better than 0.02 g/cm^2. The background under the peak is probably due to scattered neon ions.