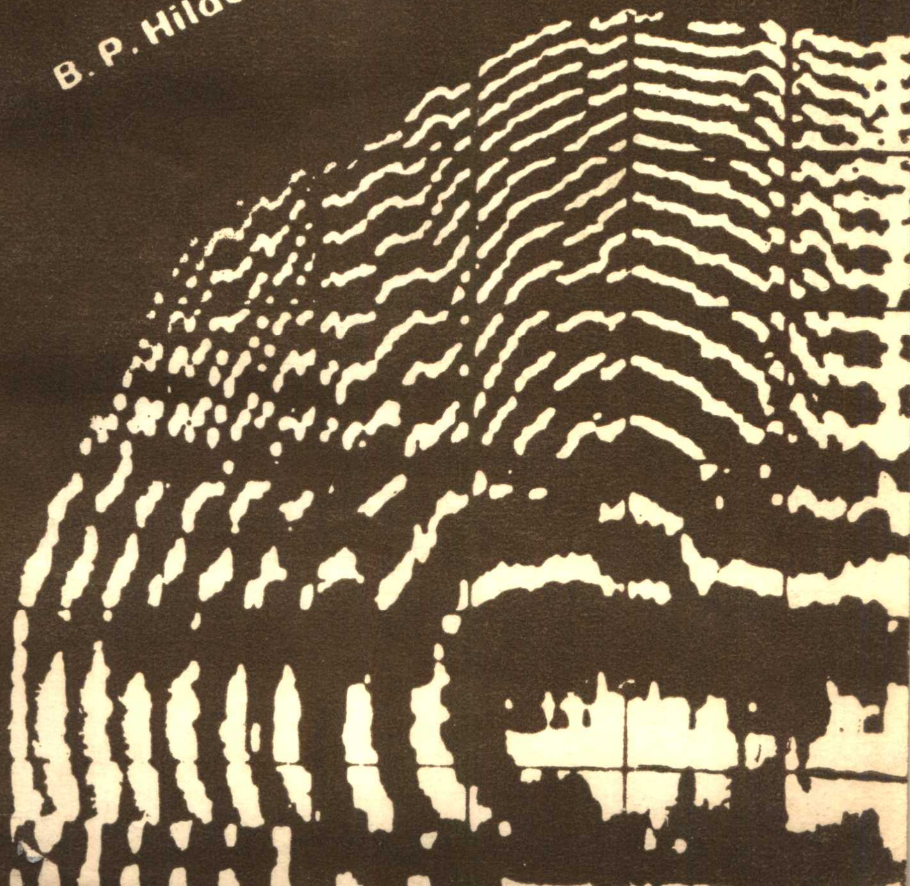
AN INTRODUCTION TO ACOUSTICAL HOLOGRAPHY

B. P. Hildebrand and B. B. Brenden



An Introduction to Acoustical Holography

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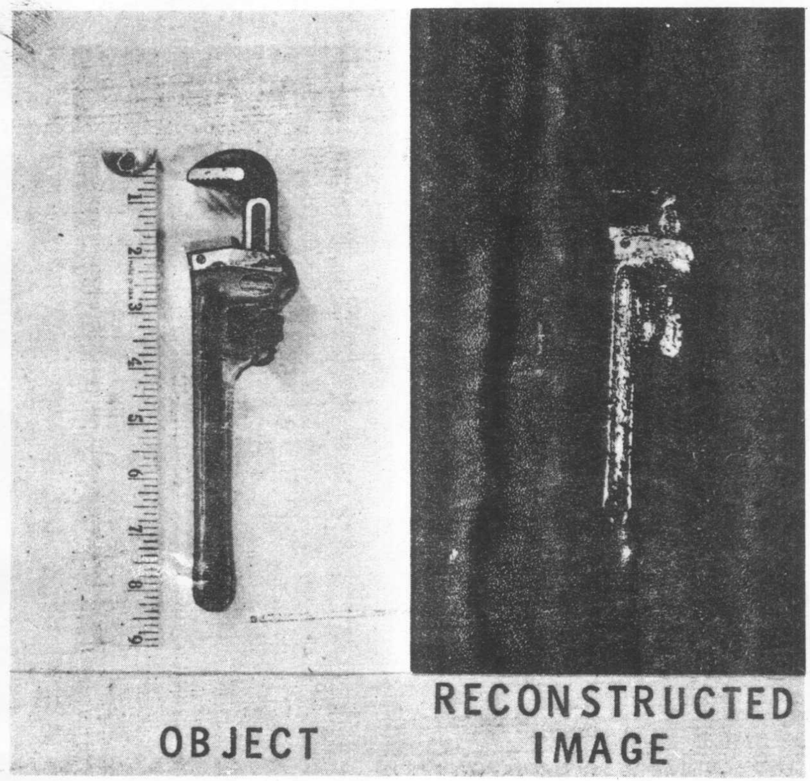

Pipe wrench—This acoustical image of the pipe wrench was produced from a source-receiver scanned hologram having an aperture of 15 x 15 cm and a line density of 33 lines/cm. The pipe wrench was insonified with 5.1 MHz sound produced by a 1-in.-diameter focused transducer.

Preface

Since the first papers by E. N. Leith and J. Upatnieks on the subject of holography appeared in 1961, there has been a virtual explosion of research activity in the field. More than 500 papers and articles on holography have appeared in the last ten years. Many applications of holography have been proposed, and some of these are beginning to enter the realm of usefulness. One of the applications that appears to hold great promise is acoustic imaging by means of holography. The first papers on this subject appeared in 1966, but already research activity in the field is burgeoning. Three symposia wholly devoted to acoustical holography have been held and the papers published in book form.

The purpose of this book is to bring together the results of research in acoustical holography, some of it as yet unpublished, under one cover so that workers in holography, nondestructive testing, medical imaging, underwater imaging, and seismic exploration can decide whether this new technique can be useful to them.

The treatment of the book requires some knowledge of differential equations and diffraction theory, but is kept as simple as possible. The first chapter includes an historical sketch of the development of holography since its invention in 1948 by Gabor. The second chapter is devoted to the development of the holographic imaging equations using the approach first used by Meier. The third chapter serves as an introduction to acoustics for those readers unfamiliar with these concepts. The following three chapters describe the various methods for obtaining and reconstructing acoustical holograms with particular emphasis on the two most-developed methods; liquid-surface and scanning. Chapter seven provides brief descriptions of other techniques that have appeared in the literature with experimental results, where available. The last chapter describes possible applications of acoustical holography to ocean surveillance, medicine, nondestructive testing, seismic exploration, and nuclear technology. Wherever possible, experimental results are shown.

We realize that a book published while research is still going on at a frantic pace is often obsolete by the time it comes out in print. Therefore, we have endeavored to use experimental results that were obtained concurrently with the writing in order that at publication it be as up-to-date as possible. All such results, even for chapters discussing holography in general, were obtained with acoustical radiation at a frequency of 3 MHz unless otherwise noted.

Much of the research reported in this book was performed at the Pacific Northwest Laboratories of the Battelle Memorial Institute, under the sponsorship of the Holotron Corporation of Wilmington, Delaware. We thank our many colleagues for allowing us to draw upon their work, in particular R. B. Smith, D. R. Hoegger, T. J. Bander, V. I. Neeley, S. C. Keeton, F. V. Richard, G. Langlois, H. Toffer, K. A. Haines, and D. S. St. John. Special thanks is due H. D. Collins and R. P. Gribble who provided a majority of the experimental results. In addition, one of us (B. P. H.) wishes to thank E. N. Leith for introducing him to this fascinating field while a student at the University of Michigan.

Thanks is due to Battelle Memorial Institute for providing the creative atmosphere and support of the Battelle Seattle Research Center during the writing of this monograph. Battelle-Northwest has also supported this effort significantly. We wish to thank G. J. Dau for his personal interest in this work and Mrs. Janice Sletager for editing the manuscript and coordinating the graphics and reproduction requirements.

Finally, we acknowledge the largesse of the University of British Columbia in the person of Miss Kathy Hardwick who typed the final manuscript and Holosonics Inc., for supplying some of the photographs for the liquid-surface holography results.

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December 1971

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Chapter 1

Introduction

1.1. FUNDAMENTAL CONCEPTS

Holography is a synthesis, for the purpose of recording and displaying an image, of two venerable branches of optics. The two branches referred to are interferometry, used in recording the hologram, and diffraction, used to display the image.

Although interference and diffraction are described in any textbook dealing with optics, they are always treated as separate topics. Only recently were the two combined to form a single branch of optics that includes holography and optical data processing. The impetus for this synthesis came from engineers and physicists working in the area of communication. In communications the analogies to interference and diffraction are modulation and demodulation. From this point of view it becomes obvious that information stored in an interference pattern (modulation) can be recovered as a result of diffraction of light by the recorded interference pattern (demodulation).

We now undertake a simplified discussion of holography based upon interference and diffraction and assume that the reader has sufficient background to accept the existence of these phenomena. Interference, in this context, is best discussed with the aid of an interferometer of the Michelson variety as sketched in Fig. 1.1. A plane monochromatic wave is split into two equal amplitude plane waves which then traverse separate paths until they are recombined. If the mirrors and beamsplitters are perfect, and if the optical path lengths are equal, the output beam will be exactly like the input beam except for the loss in amplitude incurred at the beamsplitter. A screen placed in the output beam will therefore show uniform intensity.

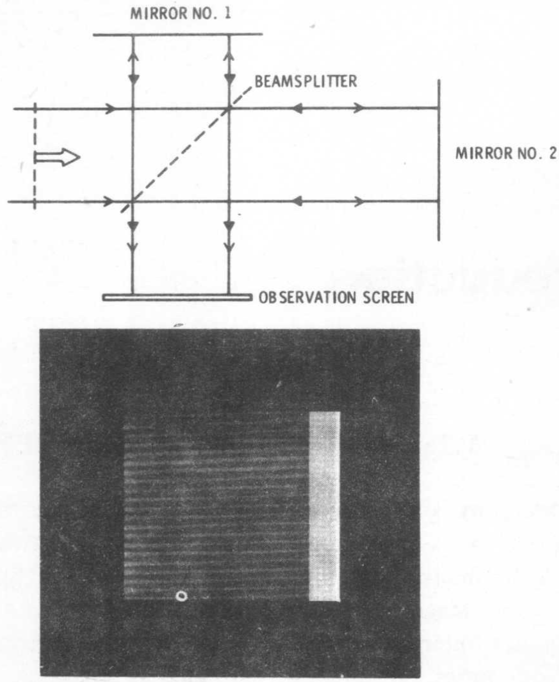

Fig. 1.1. The photograph represents the interference pattern obtained from the acoustical equivalent of the Michelson interferometer shown above it. The beam-splitter is replaced by a phase detector in which the signal from a scanning receiver is mixed with an electronic reference, and the observation screen by a film illuminated by a scanning light source modulated by the output of the phase detector.

If one of the mirrors is not quite parallel to the wave front, due to a misalignment, the reflected wave from it will recombine with the other beam to form a linear system of fringes as shown in Fig. 1.2. Destructive interference occurs wherever the path length difference between the wave fronts is an odd multiple of half the wavelength.

If one of the mirrors is replaced with a concave parabolic reflector, the interference pattern we would expect to see is shown in Fig. 1.3. Note that the ring pattern shows decreasing spacing with increasing distance from the center. The distance between rings as a function of ring number k (as counted from the center of the pattern) is approximately

$$\sqrt{R\lambda}\ (\sqrt{2k+3} - \sqrt{2k+1})$$

where R is the radius of the spherical wave and λ is the wavelength of the radiation. This type of pattern is called the Fresnel zone pattern. If we impart a tilt to the spherical wave we obtain a partial Fresnel zone pattern as shown in Fig. 1.4.

When an aperture of some kind is interposed in a collimated beam of light we might expect to see, on the screen, a pattern of light sharply defined by the shadow of the aperture. Looking closely, however, the observer notes that some light exists in the shadow zone. The study of this phenomenon is known as diffraction theory. The essence of the theory, known as Huygens' principle, is that each point on a wave front can be considered as an elementary point source radiating a spherical wave front. When the

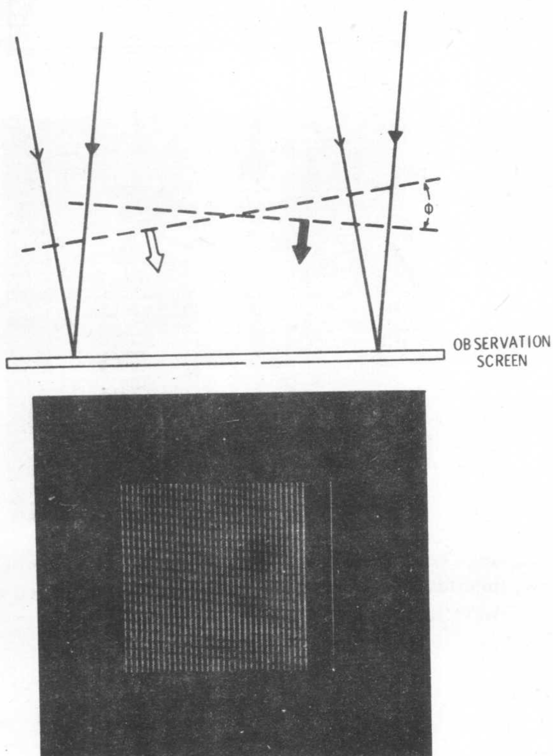

Fig. 1.2. The photograph again represents the interference pattern obtained from the acoustical equivalent of a Michelson interferometer. The difference between this result and that shown in Fig. 1.1 is a linear-spatial phase shift of the reference signal resulting in linear interference fringes.

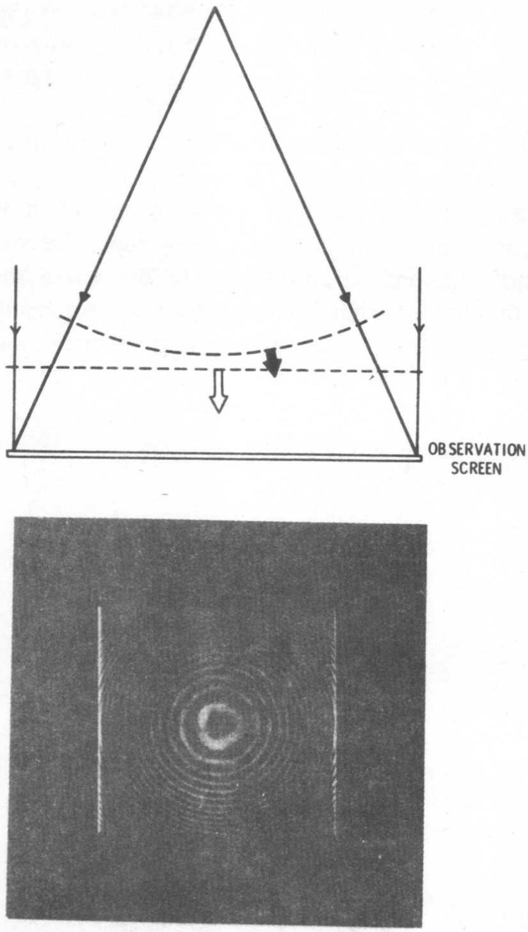

Fig. 1.3. The Fresnel zone pattern was generated by the interference of a spherical wave with a simulated plane wave in the manner described in Fig. 1.1.

elementary wavelets are summed in the prescribed manner, the result is identical to the actual wave front farther downstream. This principle is useful in analyzing the behavior of light in the presence of various types of apertures or obstructions. We now proceed to do this using as apertures the interference patterns we considered in the preceding paragraphs.

For simplicity we will assume that the interference patterns are binary, i.e., transparent or opaque. In actuality the transmission varies proportionally to $\sin^2$. First, we consider the pattern generated in Fig. 1.2. A piece of film containing this pattern is interposed in a collimated monochromatic light beam as shown in Fig. 1.5. In this figure we consider a single wavelet in the center of each transparent space. Note that each circle represents an equiphase surface advanced in phase by 2π from its neighbor to the left.

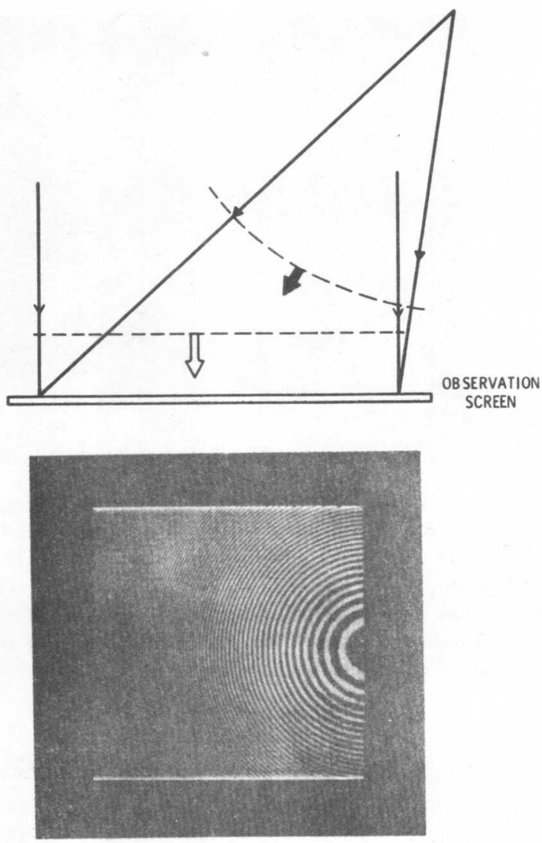

Fig. 1.4. The Fresnel zone pattern has been displaced by moving the spherical source transducer out of the aperture.

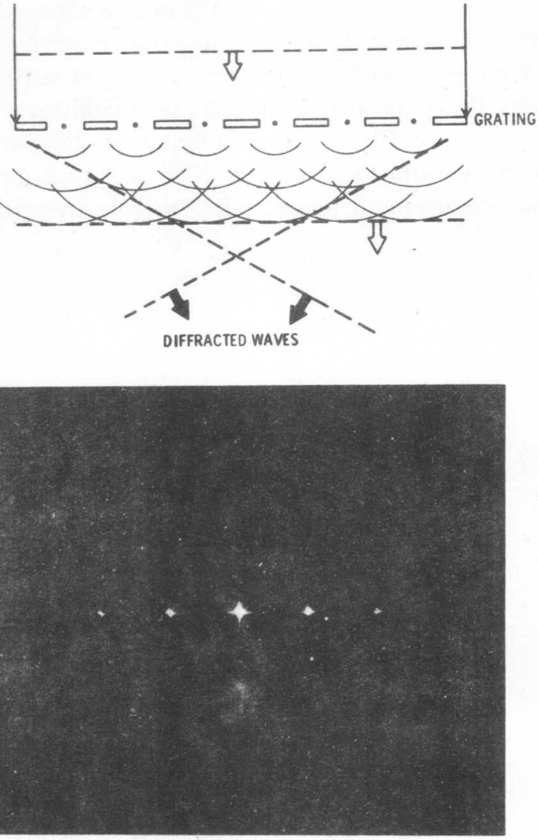

Fig. 1.5. The upper figure represents Huygens' construction from a plane grating illustrating the diffracted plane waves. The lower picture is a photograph at the focal plane of a lens showing the focused diffracted waves from the interference pattern generated in Fig. 1.2. Due to the square-wave nature of the grating second-order diffraction is also present.

The spatial separation of each such surface from the next is one wavelength λ. We can draw a plane phase front tangent to the elementary wavelet phase fronts, three of which are shown in Fig. 1.5. For the binary pattern we can draw many more plane wave fronts at ever increasing angles. If we had the actual interference pattern (i.e., $\sin^2$ transmission variation), all but these three would be attenuated. Comparing Fig. 1.5 with Fig. 1.2, we see that we have reconstructed the beams that made the interference pattern in the first place, with one exception; we have an extra beam at the conjugate angle. More will be said about this later.

The second example of an interference pattern was the Fresnel zone pattern (Fig. 1.3). Figure 1.6 shows what happens when this is illuminated. The Fresnel zone pattern is, in effect, a locally linear grating acting much the same as our first example except that the spacing varies as described previously. Hence, the locally diffracted light changes in direction and the total effect provides a spherical wave front, again duplicating the beams that caused the original interference pattern. Again, we have an extra wave of opposite curvature.

The last example we considered was that of an offset Fresnel zone pattern (Fig. 1.4). For completeness we show in Fig. 1.7 the result of introducing this pattern in a beam of light, although by now the reader no doubt anticipates the consequences.

The significance of the foregoing discussion is that interferometry has always had the capability of recording a wave front and later reconstructing it. It is remarkable that this fact was not grasped much earlier than it was. Our three examples of interference patterns were carefully chosen to lead the reader to understand, on physical grounds, how and why holography works. The first example (Fig. 1.2) was intended to demonstrate both interference and diffraction. The second example (Fig. 1.3), a slightly more complicated situation, was chosen to show how Gabor holography works and why it is not too successful. Using the Gabor approach, one is reconstructing three beams of light, all occupying the same volume. That is, if we consider Fig. 1.6 and imagine that we are looking for a replica of the spherical wave used in making the interferogram, we are also forced to look at the plane wave and the converging extraneous wave, both of which tend to mask the light from the desired wave.

The third example, Fig. 1.4, shows how this difficulty is overcome by using an offset in the spherical beam. The same result can be produced by bringing the plane reference beam in at an angle, although in this case the interference pattern is not a circular Fresnel pattern. In this case, all three diffracted beams are separated in space, thus completely solving the problem of overlap.

To make these discussions conform to what one generally likes to think of as holography, one further step is required; namely, to record and display an image of a complicated object. This step only requires that we accept Huygens' principle which states that any arbitrary wave front representing the light reflected from a complicated object can be considered to