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INTRODUCTION TO HOLOGRAPHY

by CAPT MELVIN C. WATKINS, AF Res

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INTRODUCTION TO HOLOGRAPHY

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Capt Melvin C. Watkins, AF Res

Office of Aerospace Research ★ United States Air Force

Arlington, Virginia 22209

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I. INTRODUCTION

It is the intent of this paper to provide a descriptive definition of a term that is one of the latest contributions of science to the ever-growing technical vocabulary. "Holography," a word which for many years was confined to the world of optics, is rapidly becoming commonplace throughout the scientific community. The concept of holography and its nomenclature were introduced in 1948 by Dennis Gabor. (1) Gabor demonstrated that the amplitude and phase information contained within the image of an illuminated object could be photographically recorded, stored, and retrieved. He called the recording a hologram and the process holography, choosing as a prefix the Greek word, *holo,* which means whole, to differentiate his photographic technique from conventional ones which use only amplitude information.

A significant aspect of preserving the phase information in a photographic recording is that the reconstructed image is displayed in three dimensions. A properly constructed hologram can produce in its three-dimensional image not only a stereo effect, but also all of the parallactic effects of the original scene, thereby allowing one to see behind objects by looking around them.

To supplement my first statement, the intent here is to convey, as an introduction to holography, an understanding of the holographic process by discussing basic concepts and describing a few of the most attractive applications. Presentations of analytical expressions have been kept to a minimum and, it is hoped, the concepts presented in a simplified manner. Unfortunately, the subject in depth is quite complex and, for those individuals unfamiliar with optical interferometry, exceedingly difficult to grasp. Since it is true that the holographic technique is intimately entwined with the principles of optical interference and diffraction phenomena, this author feels that a recap of these principles would be appropriate and has therefore reviewed them in the following section.

II. OPTICAL INTERFERENCE AND DIFFRACTION

In the study of physical optics, the point of view is taken that light propagates in a wave motion and is thereby identified by its amplitude and phase characteristics. When two or more light beams intersect in space, the principle of superposition applies, resulting in an interference effect. The principle of superposition states that the resultant displacement at any point and at any instant may be found by adding the instantaneous displacements that would be produced at the point by the individual wave trains if each were present alone. (2) For light emitted from two sources generating waves in unison, there will be points in space where the phases of the waves add, producing a reenforcement of the amplitudes, while at other points in space the phase relationship will produce a cancellation of the amplitudes. This interference effect will be manifest in the appearance of bright and dark areas when viewed on a screen placed in the path of the light beam. The highlights of the classical demonstration and analysis by Young of the interference effect illustrate the generation of fringes resulting from the principle of superposition. (See Figure 1.)

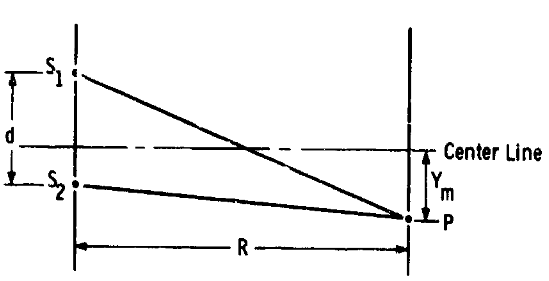

Figure 1. Young's Experiment.

Consider S_1 and S_2 in Figure 1 as coherent light sources generating waves which intersect in space at the point P. For brightness to occur at this point, the light waves must be in phase; therefore, the path lengths must be an integral number of wavelengths long. According to this requirement and the configuration of Figure 1, the relationship of the parameters shown to the occurrence or spacing of bright areas is:

$$Y_m = m\frac{R\lambda}{d} \qquad (1)$$

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* *Prepared by Capt Watkins while on active duty with the Engineering Sciences Division, DCS/Plans & Programs, Hq OAR.*

where

Y_m = distance from the center axis

m = integer

R = distance from source to observation plane

λ = wavelength of light

d = distance between sources

Hence for m = 0 (zeroth fringe), a bright area will occur on the center line, as illustrated in Figure 1. The purpose of this presentation is to emphasize the relationship of the fringe spacing, Y_m, or the spatial frequency, $1/Y_m$, to the geometrical relationship between the sources and the distance R to the observation plane where the fringes are observed.

The second basic optical phenomenon descriptive of the holographic process is that of diffraction. Diffraction is an effect which appears to cause a light beam to bend around an opaque object. This effect can be explained on the basis of Huygens' principle which states that every point of a wave front may be considered the source of small secondary wavelets which propagate in all directions. Thus, at the edge of an opaque object, the light wave acts as a secondary source directing waves in all directions and providing an illumination in areas of geometrical shadow. Since every portion of the original wave acts like a secondary source, a very complex interference pattern is produced at observation planes in the path of the reflected rays. The fringes generated by this type of interference effect produce what is referred to as a diffraction pattern. A close look at the analysis for the spacing between the fringes of a diffraction pattern will show an identical geometrical relationship between sources and observation-plane distances as shown by the interference effect described earlier. Although this relationship is obvious, it is not generally emphasized, and is brought to the reader's attention because of its significance in a later reference describing the holographic process.

Note that the separation between the fringes, Y_m, is inversely proportional to the "d" dimension of the space between the wavelet sources. Since the diffraction effect is generated from sources which are adjacent illuminated points on an object, the value of d is small, whereas in the cases of those sources generally considered in producing the interferometry effect, the d dimension would be several orders of magnitude larger. Therefore, one should recognize that the fringe spacings for the diffraction pattern will be greater than those for the interferometric effect.

In terminology common to many holographic discussions, the reciprocals of the fringe spacings are referred to as spatial frequencies; therefore, it is clear from the previous discussion that the spatial frequency of the diffraction pattern will be lower than that of the interferometric pattern. This point is discussed below in the description of the holographic process.

III. THE HOLOGRAPHIC PROCESS

The holographic process originally proposed by Gabor used a point source (a means of producing a spatially coherent light beam of low quality) to illuminate a transparent object which generated a diffraction pattern. This diffraction pattern, when photographed, produced a hologram. Recall that the hologram is a recording of the amplitude and phase information contained within the reflected energy from the object. Illuminating this transparency with a point source of light reconstructed a three-dimensional image. Unfortunately, due to the low purity of the light coherency, the low-quality image inherent in the original technique, and restrictions on those objects for which the Gabor technique was useful, the concept generated limited interest. The advent of the laser, combined with an analysis by E. Leith and J. Upatnieks in 1962, (3) provided the motivation for renewed interest in the subject. The insight of these two men, apparent in their analysis, made it possible to raise the quality of the holographic technique to a highly acceptable level. Their approach describes the process from a communication-theory viewpoint, thereby permitting the application of electronic-system techniques to optical procedures, in generating holograms, to enhance the signal-to-noise ratio of the reconstructed image. One of the major suggestions was to incorporate a reference beam in constructing the hologram so that it would perform as does a carrier frequency in a communication system. By this process, the reference beam acts as the second source in the optical interference process, generating a high spatial frequency. The diffraction pattern produced by the object would have, for reasons given previously, a low spatial frequency modulating the reference or carrier frequency.

In order to understand the basic procedure in constructing a two-beam hologram, let us consider a coherent source of light, such as the laser, which illuminates the object and a mirror, both of which redirect the light to a photographic plate, as shown in Figure 2. Each point on the object, acting as a source light, generates a diffraction pattern in the plane of the photographic plate. The light wave reflected from the mirror, acting as a reference beam or carrier, adds to the waves reflected from the object to produce an interference pattern, also in the plane of the photographic plate. Here the condition exists where the interference pattern producing closely spaced fringes is modulated or altered by the larger-spaced fringes produced by the diffraction effect generated from the object. To reconstruct the image, the hologram, which now looks like diffraction grating, is illuminated by a coherent source. The image, when viewed through the hologram, exists as the original scene.

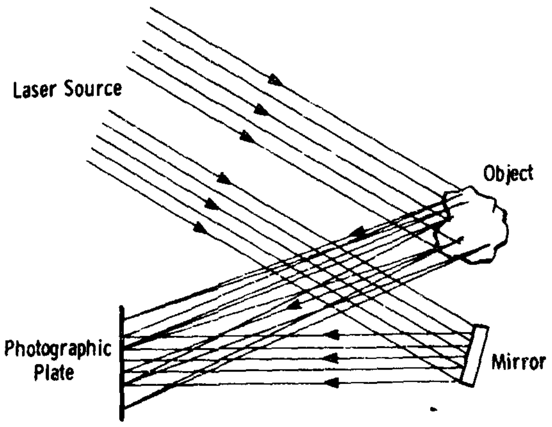

Figure 2. A Two-Beam Hologram

Leith (4) has presented this operation in very simple mathematical terms which are given below as an additional aid in understanding the concept.

The reference beam is expressed as:

$$u_o = a_o \cos(\omega t - \alpha x) \qquad (2)$$

where αx represents a phase shift across the recording plate. The diffraction pattern generated by the object is of the general form of:

$$u = a(x,y) \cos[\omega t + \phi(\alpha, y)] \qquad (3)$$

The photographic process acts as a square-law device recording the function

$$\overline{(u_o + u)^2} = \tfrac{1}{2}a_o{}^2 + \tfrac{1}{2}a^2 + a_o a \cos(\alpha x + \phi) \qquad (4)$$

In the reconstruction process, the emergent light is:

$$a_o(\tfrac{1}{2}a_o{}^2 + \tfrac{1}{2}a^2)\cos(\omega t - \alpha x) + \tfrac{1}{2}a_o{}^2 a \cos(\omega t + \phi) + \tfrac{1}{2}a_o{}^2 a \cos(\omega t - 2\alpha x - \phi) \qquad (5)$$

Realizing that the α and ϕ terms are functions of the (x,y) coordinates, one can readily see that the emergent light possesses the same term as that given originally for the light reflected by the object, except for the constant coefficient. Therefore, looking through the photographic plate, one would observe a replica of the original subject.

Up to this point, the discussion has ignored the fringe effect within the depth of the recording emulsion which is permissible whenever a low spatial frequency exists. However, this is not always the case, and some very interesting effects occur by utilizing the film thickness in the recording process. In these techniques, the reference beam is directed to the rear of the photographic plate as opposed to exposing the front side, as previously described. Holographic construction, in this way, is referred to as a reflection type, in contrast to those previously discussed, which are commonly known as the transmission type. The reflection-type hologram, due to the relative positions of the light sources, generates a fringe pattern whose spacings are less than the emulsion thickness, thereby producing a recording in the depth of the emulsion. These stratified layers act as resonant structures generating optical interference filter effects. A hologram of this type, by the nature of its resonant structure, possesses extreme wavelength selectivity, allowing the use of white light for reconstruction. (5)

IV. APPLICATIONS AND LIMITATIONS

The major practical applications of the holographic process have been those related to interferometric analysis. To appreciate the advantages offered by the holographic process, a review of a conventional interferometer is presented below. The particular interferometer illustrated in Figure 3 is known as the Mach-Zehnder type. In the initial conditions, the optical path lengths in the two legs are made equal, and the rays are made parallel after recombining at the beam splitter, S2. With these conditions, perfect interference will occur at the observation plane, and the area at that plane will be uniformly illuminated. The introduction of a specimen in the test chamber will produce changes in the path length of the light beam in one leg, generating an interference pattern from which an analysis of the specimen can be made by a study of the fringe spacings. The requirements on the optical quality of this mechanism are quite stringent in order to produce a pattern at the observation plane either void of fringes, or to produce an orderly pattern of fringes for the initial set-up. By the use of holographic techniques, a reference pattern can be produced which masks the effects of undesirable fringes generated from imperfections within the system.

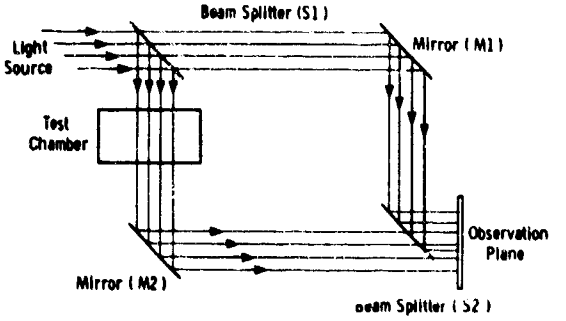

Figure 3. Mach-Zehnder Interferometer

An example of this type of problem and its solution by the application of holography is given by Heflinger, et al, (6) where the interference pattern produced by the hot gases within an automobile dome lamp is illustrated. The low-quality glass of the bulb in a conventional interferometer would produce such a complex contour of fringes that the thermal diffractions would be extremely difficult, if not impossible, to observe. However, with the holographic interferogram, these are clearly seen.

This same approach is applied to another technique reported by Powell and Stetson, (7) where the differential interference pattern is observed for structural vibrational analysis. In this application, the image produced by the hologram is a contour map of constant vibration amplitudes. The advantage of this technique lies in its permitting one to analyze large models, such as aerodynamic or hydrofoil structures, without having to be attached physically to these structures.

The principles of holographic interferometry can also be applied in a slightly different manner in solving problems of pattern-recognition application. As shown in the previous discussion, the use of a hologram as a spatial filter enables one to measure the similarity or dissimilarity of a comparison pattern. In the previous case, the desire was to record and measure the magnitude of this difference whereas, in pattern-recognition application, one merely desires to know whether or not a similarity exists. A very interesting use of this technique was reported by Horvath et al (8) for fingerprint selectivity. The authors reported that experimental results have shown the recognition to be extremely selective, with 91% of the maximum selectivity occurring with 50% of the fingerprint obscured. They also indicated the selectivity was relatively insensitive to lateral, vertical, and longitudinal positioning of the print in the system.

More dramatic applications of holograms are being made with the construction of three-dimensional color images. A technique for producing this effect was reported by Upatnieks et al. (9) The hologram is a reflectance type in which three primary colors are used as references and illuminators for the subject. As discussed in a previous section of this paper, the reflectance-type hologram produces surfaces or interfaces within the depth of the emulsion so as to act as an effective interference filter. In the reconstruction process, the hologram can be illuminated with white light. The hologram will selectively reflect only those wavelengths used in producing the filter effect. Thus, an image in full color is viewed.

A detailed analysis of the effect concerning the emulsion thickness has been made by Leith et al. (10) In this analysis, the authors show that the orientation and wavelength used in the construction of the hologram, combined with variations of these parameters in the reconstruction process, establish certain conditions which must be satisfied in order for an image to occur. Therefore, the use of a thick emulsion in the holographic process can provide the means of selectivity to store and recover data. By rotating the photographic plate between exposures, a hologram movie was produced by Leith et al (10) to demonstrate this storage capability.

V. SUMMARY

The principle of holography entails the photographic recording of the complex interference pattern generated by the illumination of an object with a coherent-light source. The image produced by the illumination of the hologram contains all of the geometrical characteristics of the original scene; that is, it would appear as though one were looking through a stained-glass window. This characteristic is appealing for applications in entertainment and training devices where a high degree of environmental simulation is desired. As a tool for diagnostic applications, the differential interferometry technique has aroused considerable interest. Here, as a recording of interference patterns produced by the geometrical configuration of an object, the hologram can highlight minute deformations in the shape of the test specimen. The technique can also be applied to eliminate the effect of optical deficiencies within interferometric systems, thereby allowing increased sensitivities with low-cost components.

The difficulties that must be faced in implementing the holographic process are due to the extreme mechanical rigidity required of the system during the exposure period, and the limitations imposed by the relatively short coherent length presently provided by laser sources. Needless to say, human ingenuity and determination will undoubtedly overcome these barriers and achieve the goals that theory prophesies for this unique concept, thereby opening still another door in the world of engineering technology.

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13. ABSTRACT

This monograph seeks to provide a descriptive definition of a term, "Holography," which is one of the latest contributions of science to the ever-growing technical vocabulary. Holography, as such, reflects a process whereby the amplitude and phase information contained within theimage of an illuminated object can be photographically recorded, stored and retrieved. The recording, itself, is called a hologram.

To further an understanding of the holographic process, the author discusses basic concepts, and describes a few of its most attractive applications.

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