Chapter 2

Review and Basic Principles

2.1 Introduction and Concept of Holographic Imaging

In all conventional imaging techniques a picture of a three-dimensional scene is recorded on a light-sensitive surface through a lens system. Merely the intensity distribution in the original scene is recorded. As a result, all information on the relative phases of the light waves from different points of the scene is lost. The unique characteristic of holography is the idea of recording the complete wave field, that is both the phase and the amplitude of the light waves scattered by an object. Since all recording mediums respond only to the intensity, it is necessary to convert the phase information into variations of intensity. This is done by using coherent illumination and having a reference wave incident on the recording medium along with the wave scattered by the object. It is apparent that what is recorded on the recording medium is the interference pattern produced by the two waves. The intensity at any point in this pattern depends on the phase as well as the amplitude of the original object wave. Accordingly, the processed recording medium, which is called a hologram, contain information on both the phase and the amplitude of the object wave. This information is in a coded form, and the hologram itself bears no resemblance to the object. Illumination of the developed hologram by the reference
beam alone reveals a three-dimensional image, which is essentially identical to the 
original object as viewed in reference light. Observing the holographic image of the 
object is exactly like looking at the object through the window formed by the plate 
with full parallax and look-around capability. The object wave is reconstructed when 
the grating formed in the recording medium is diffracted by reference wave.

2.2 Historical Development of Optical Holography

The science of holography has taken some curious turns in its relatively short 
50-year history. The time divides itself naturally into five periods: The first could be 
considered as precursor stage, when the aim was to record wavefronts diffracted 
from crystals that had been irradiated with x-radiation or electron waves. If 
reconstruction with visible light wave successful, a highly magnified image of the 
crystal lattice would result. Recording the phase of the radiation was a difficult 
problem that was soluble only for rather special cases.

In 1948, Gabor [4,5,6] developed a way to introduce a coherent background or 
reference wave and the second period began. The third stage began in the early 
1960’s, when Leith and Upatnieks [7,8,9] demonstrated high-quality holographic 
imagery with the laser. In this period holographic interferometry technique is 
developed, and after that the development of holography was very tempestuous. Its 
theoretical and experimental foundations were laid in this period.

The fourth period begin in the early of 1970’s, where the researchers started to 
use electronic camera as a recording medium. This is the period we called electronic 
holography. The holograms are recorded with electronic camera and reconstruction
with optical or analog electronic methods. ESPI and DSPI are the technique been produced during this period.

The fifth period begin with the use of digital electronic in holography. Now the holograms are recorded with the CCD camera and numerically reconstructed without using any light source.

2.2.1 Early holography

Holography is a method of recording and reconstructing wavefronts that is based on recording the distribution of the intensity of an interference pattern formed by an object wave and a reference wave coherent with it. A recorded interference pattern is called a hologram. The principles of holography were discovered by Gabor in an attempt to improve the resolving power of the electron microscope [4,5]. He proposed to record phase information of electron waves by the superimposition of a coherent reference wave. Although unable to demonstrate the validity of his principle with electron waves, he was able to do so with visible light. This was the beginning of holography.

Interest in holography continued strong for several years afterward, and produced some notable pioneers. Gordon Rogers carried out the first approach to optical holography with a high-pressure mercury lamp in 1952 [10]. He explored the new technique in many ways, uncovering new ramifications and new insights. One of his best known contributions is his extensive development of holographic image-forming principles in terms of Fresnel zone-plate theory [10]. His work had become the forerunners of much of the holographic investigation carried out more than a decade later with a laser. M. E. Haine, Jame Dyson and T. Mulvey applied
holography to electron microscopy [11,12]. In USA, Kirkpatrick, Baez and El-Sum, became interested in holography in its application to x-ray imagery [13]. In Germany, Adolf Lohmann [14] first applied communication theory techniques to holography.

The interest in holography waned in the middle 1950's due to the relatively poor imagery. However, optical holography in 1950's continued to be carried out with Gabor's original in-line arrangement i.e. source and object were placed on optic axis as shown in Figure 2-1(a). A plane wave of monochromatic light passes through a photographic transparency, which is the object. Part of the light will be diffracted by the image recorded on the transparency, and part of the light will pass through the transparency without being scattered.

The directly transmitted light serves as the reference wave. Since its amplitude and phase do not vary across the photographic plate, its complex amplitude can be written as a real constant $a_r$. The diffracted light, which caused by the transmittance variation in the object. The complex amplitude of this wave at the photographic plate can be written as

$$\Psi_o(x,y) = a_o(x,y)\exp[-i\Phi(x,y)]$$  \hspace{1cm} (2.1)

where $a_o(x,y)$ is the real amplitude of the object wave, where $a_o(x,y)\ll a_r$, and $\Phi(x,y)$ is its phase. The complex amplitude $\Psi_o(x,y)$ contains all the information about the spatial structure of light waves. The resultant complex amplitude at any point on the photographic plate is the sum of these two complex amplitudes. The intensity at this point is
Figure 2-1 Optical system used to (a) records an in-line hologram; (b) reconstructed the image from an in-line hologram.
\[ I(x, y) = |a_r + \Psi_o(x, y)|^2 \]
\[ = a_r^2 + a_o^2(x, y) + a_r \Psi_o(x, y) + a_r \Psi_o^*(x, y) \]  

(2.2)

where * denotes a complex conjugate.

For simplicity, we assume that this photographic plate has been processed so that its amplitude transmittance \( t(x, y) \) is linear proportional to \( I(x, y) \) as

\[ t(x, y) = t_b + \beta I(x, y) \]
\[ = t_b + \beta \left[ a_r^2 + a_o^2(x, y) + a_r \Psi_o(x, y) + a_r \Psi_o^*(x, y) \right] \]  

(2.3)

where \( t_b \) is a constant background transmittance and \( \beta \) is a parameter determined by the photosensitive material used and the processing conditions. The developed film is referred to as a Gabor hologram or an in-line hologram.

The object wave is reconstructed by illuminating the hologram, which is replaced in the same position as the original photographic plate, with the same laser light used in recording as shown in Figure 2-1(b). The complex amplitude transmitted by the hologram can be written as

\[ \Psi_T(x, y) = a_r t(x, y) \]
\[ = \left( t_b + \beta a_r^2 \right) a_r + \beta a_r a_o^2(x, y) + \beta a_r^2 \Psi_o(x, y) + \beta a_r^2 \Psi_o^*(x, y) \]  

(2.4)

Four terms are obtained, which have the following meaning:
1. \((\mathbf{\epsilon}_b + \beta a_r^2) a_r\) Zeroth diffraction order, the reference wave is multiplied by a constant factor

2. \(\beta a_r a_c^z(x,y)\) Broadened zeroth diffraction order, modulated by \(a_c^2(x,y)\).
   Since it has been assumed that \(a_c(x,y) \ll a_r\), this term is small compared to the other term and it can be neglected.

3. \(\beta a_r a_c^z\Psi_o(x,y)\) Direct image (virtual).

4. \(\beta a_r a_c^z\Psi_o^*(x,y)\) Conjugate image (real)

The third term, except for a constant factor, is identical with the complex amplitude of the scattered wave from the object that was originally incident on the photographic plate. This wave reconstructs an image of the object in its original position, and it is a virtual image.

The fourth term corresponds to a wavefront that resembles the original object wavefront but in the opposite curvature. This wave converges to form a real image at a distance \(d\) in front of the hologram.

The main disadvantages of in-line hologram are the disturbed reconstruction due to the bright reference beam and the twin images, virtual and real image along the same line of sight. So while viewing one of them, an observer sees it superposed by an out-of-focus image of the other one. The presence of this unwanted image constitutes the most serious limitation of the in-line hologram. These drawbacks are avoided by the off-axis arrangement, which was proposed by Leith and Upatnieks [7,8,9].
2.2.2 High quality holographic imaging

After a decade destined for obscurity, this bleak prospect brightened in the early 1960’s with work carried out at the University of Michigan Institute of Science and Technology. Holography was born again in 1962, when Leith and Upatnieks [7] used newly available HeNe lasers, which had been invented by that time, to produce the first high-quality, three-dimensional images for holography, and when they proposed their split-beam (also called two-beam or off-axis) method of preparing holograms. Using this method, the reference and object waves are brought together at an angle, to form a fine fringe pattern.

Figure 2-2(a) is a schematic diagram of the off-axis arrangement for hologram formation. A reference wave is incident on the photographic plate along with the wave scattered by the object. The object wave can be regenerated from the hologram merely by illuminating it once again with the reference wave, as shown in Figure 2-2(b).

The complex amplitude of the object and reference waves on the hologram plane \( z = 0 \) can be expressed as follows:

Object wave: \[ \Psi_o(x, y) = a_o(x, y) \exp[-i\Phi(x, y)] \] (2.5)

Reference wave: \[ \Psi_r(x, y) = a_r \exp[2\pi f_y y] \] (2.6)

where \( f_y = \sin \theta_r / \lambda \) is the spatial frequency of the reference wave; \( a_o(x, y) \) and \( a_r \) are the amplitudes of the object and reference waves, respectively; and \( \Phi(x, y) \) is the phase of the object wave.
Figure 2-2  (a) Recording a hologram. The photographic plate records the interference pattern produced by the light waves scattered from the object and a reference wave reflected to it by the mirror; (b) Reconstruction of the image. The hologram after processing is illuminated with the reference wave from the laser. Light diffracted by the hologram appears to come from the original object.
Consequently, as in the Gabor hologram, the resultant intensity at the hologram plane is

\[ I(x, y) = a_o^2(x, y) + a_r^2 + \Psi_o a_r e^{-i2\pi f_{xy}} + \Psi_o^* a_r e^{i2\pi f_{xy}} \]  

(2.7)

and its amplitude transmittance \( t(x, y) \) is

\[ t(x, y) = t_b + \beta I(x, y) \]
\[ = t_b + \beta \left[ a_o^2(x, y) + a_r^2 + \Psi_o a_r e^{-i2\pi f_{xy}} + \Psi_o^* a_r e^{i2\pi f_{xy}} \right] \]
\[ = t_b + \beta \left[ a_o^2(x, y) + a_r^2 + 2\beta a_r a_o(x, y) \cos[2\pi f_{xy} + \Phi(x, y)] \right] \]  

(2.8)

where * denotes a complex conjugate. Equation (2.8) clearly shows that the hologram consists of a set of "carrier" interference fringes of spatial frequency \( f_y \), which are modulated in amplitude by \( a_o(x, y) \) and in phase by \( \Phi(x, y) \).

When the hologram is illuminated with the reference beam \( \Psi_r(x, y) \) the image is reconstructed, as shown in Figure 2-2(b). The distribution of light transmitted through the hologram is given by

\[ \Psi_T(x, y) = \Psi_r(x, y) t(x, y) \]
\[ = \Psi_r \left( t_b + \beta a_r^2 \right) + \Psi_r \beta a_o^2(x, y) + \beta a_r^2 \Psi_o + \beta a_r^2 \Psi_o^* e^{i4\pi f_{xy}} \]  

(2.9)

The expression for complex amplitude of the transmitted wave contains four terms. The meaning of each term is the same as described for in-line hologram. However, in
off-axis hologram, the fourth term includes an exponential factor $\exp(i4\pi f_y \cdot y)$, which indicates that the conjugate wave is deflected from the $z$-axis at an angle approximately twice that which the reference wave makes with it.

Accordingly, the real and virtual images are formed at different angles from the directly transmitted beam and from each other. If the offset angle $\theta$ of the reference beam is made large enough, the three will not overlap. This method therefore eliminates all the major drawbacks of Gabor’s original in-line arrangement.

The publication of Leith and Upatnieks’ work [7,8,9] created an explosive interest in the field and the development of holography after that was very intensive. By 1965-1966, its theoretical and experimental foundations were laid and in the following years, holography developed mainly along the path of improving its applications. Progress continues to be made in the development of new materials and techniques sustaining a high level of interest in holography and its technical, commercial and artistic applications. Today holography is widely known as a practical means for storing wavefronts in a record from which the wavefronts may later be reconstructed.

2.3 Holographic Interferometry

Holographic recording and reconstruction of a wave field is sufficiently precise so that holographically reconstructed fields can be compared interferometrically either with a field scattered directly by the object, or with another holographically reconstructed wave field. Holographic techniques permit the measurement of displacements and deformation without contact [1,14,15].
In conventional holographic interferometry, two coherent wave fields, which are reflected by two different states of the object, are made to interfere. This interference is achieved in double-exposure holography by recording of the two wave fields on a single holographic plate. If the developed holographic plate is illuminated with a wave similar to the reference wave used in the process of recording, a holographic interferogram is formed. The fringe pattern represents the phase difference between the interfering waves. From the interference phase together with the sensitivity vectors, which are given by the geometrical arrangement of the optical components, the deformation field is determined.

In double exposure holographic interferometry two wavefronts scattered by the same object are recorded consecutively onto the same holographic film \([1, 14, 15]\). The two wavefronts correspond to the different states of the object, one in an initial condition, Figure 2-3(a), and one after the change of physical parameter, Figure 2-3(b), e.g. by altering the object loading.

Let the complex amplitude of the first wavefront at an object point \((x, y)\) be

\[
\Psi_1(x, y) = a(x, y)e^{i\Phi(x, y)}
\]

(2.10)

which is holographically recorded. \(a(x, y)\) is the real amplitude and \(\Phi(x, y)\) is the phase distribution. The phase distribution varies spatially in a random manner due to the microstructure of the diffusely reflecting or refracting object.

The variation of a physical parameter to be measured, e.g. the object shape due to the deformation of an opaque change in the phase distribution at point \((x, y)\) by \(\Delta\Phi(x, y)\). So the complex amplitude of the second wavefront to be recorded holographically onto the same film is
Figure 2-3  Recording (a), (b), and reconstruction (c) of a double exposure holographic interferogram.
\[
\Psi_2(x, y) = a(x, y)e^{i[\Phi(x, y) + \Delta\Phi(x, y)]}
\] (2.11)

After development of the holographic film both wavefronts are reconstructed simultaneously, Figure 2-3(c). They interfere and give rise to a stationary intensity distribution

\[
I(x, y) = |\Psi_1(x, y) + \Psi_2(x, y)|^2 = \Psi_1^2 + \Psi_2^2 + \Psi_1^*\Psi_2 + \Psi_1^*\Psi_2^*
= 2a^2(x, y) + a^2(x, y)e^{-i\Delta\Phi(x, y)} + e^{i\Delta\Phi(x, y)}
= 2a^2(x, y)[1 + \cos \Delta\Phi(x, y)]
\] (2.12)

Equation (2.12) represents the irradiance of the object, \(a^2(x, y)\), modulated by a cosine-shaped fringe pattern \(2[1 + \cos \Delta\Phi(x, y)]\). The change of the phase \(\Delta\Phi(x, y)\) is called the interference phase. Bright fringes are the contours, where the interference phase is an even integer multiple of \(\pi\). Dark fringes are the contours corresponding to odd integer multiple of \(\pi\). Clearly, if the interference phase changes too rapidly from one observing point to the next, so that the sampling theorem is violated, we will recognize only a more or less random intensity distribution, which cannot be evaluated any more.

In various applications, the interference phase \(\Delta\Phi(x, y)\) may be related to physical quantities such as displacement, rotation, strain, bending moment, vibration amplitude, temperature, pressure, mass concentration, electron density, or stress.
2.4 Holographic Recording Materials

Recording materials suitable for holography should exhibit a number of properties, like a spectral sensitivity well matched to available laser wavelengths, a linear transfer characteristic, high resolution, and low noise. They should be easy to handle, reusable and inexpensive. No material has been found so far meet all these requirements. When the coherent light of the HeNe laser became accessible for holography the silver halide photographic emulsion was the only material readily available that provided the necessary high resolution and sufficient sensitivity to the red light of this laser. Since then, lasers generating radiation of shorter wavelengths have been developed, making other light-sensitive processes useful for hologram recording. A great number of non-silver photographic materials have been improved or adapted for holography. A selection of recording materials is given in Table 2-1.

Today, the most widely used recording materials still are the silver halide photographic emulsions because of their high sensitivity and their commercial availability. In addition, they can be dye sensitized and their spectral sensitivity matches the most commonly used laser wavelengths. Emulsions of silver halide have resolutions as high as 5000 lines/mm. With these emulsions, holograms with angle between the reference and the object waves of nearly 0° to 180° can be recorded. The main disadvantages are the wet chemical processing and the single use.

Dichromated gelatin is used as a gelatin layer containing a small amount of dichromate. By a photochemical reaction this medium becomes harder on exposure to light. If the unhardened gelatin is washed out with warm water, a relief image is formed.
<table>
<thead>
<tr>
<th>Material</th>
<th>Reusable</th>
<th>Processing</th>
<th>Spectral sensitivity (nm)</th>
<th>Resolution (mm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver halide</td>
<td>No</td>
<td>Wet chemical</td>
<td>400-700</td>
<td>&gt;10000</td>
</tr>
<tr>
<td>Dichromated gelatin</td>
<td>No</td>
<td>Wet chemical</td>
<td>350-580</td>
<td>3000</td>
</tr>
<tr>
<td>Photoresists</td>
<td>No</td>
<td>Wet chemical</td>
<td>UV-500</td>
<td>200-1500</td>
</tr>
<tr>
<td>Photochromic</td>
<td>Yes</td>
<td>None</td>
<td>UV-650</td>
<td>&gt;5000</td>
</tr>
<tr>
<td>Phototherma-plastics</td>
<td>Yes</td>
<td>Charge</td>
<td>300-700</td>
<td>500-1200</td>
</tr>
<tr>
<td>CCD</td>
<td>Yes</td>
<td>None</td>
<td>400-1000</td>
<td>≈100</td>
</tr>
</tbody>
</table>

Photoresists are light-sensitive organic films that yield a relief image after exposure and development.

The photopolymers are organic materials that can be activated through a photosensitizer to exhibit thickness and refractive index changes due to photopolymerization.

Photochromics undergo reversible changes in color when exposed to light. Photochromics have limited use due to their low sensitivity and low diffraction efficiency.

Dichromated gelatin, photoresists, photopolymers, and photochromics are not readily available for use but must be prepared by the user before application.

Photothermoplastics are widely used in holographic interferometry, mainly because they are reusable and avoid the wet chemical processing.
The time and effort of development of the silver halide emulsion is especially detrimental when repetitive inspection in an industrial environment is needed. For this reason, during the period of the late 1960’s and early 1970’s there was interest by many workers in utilizing laser and holography techniques in conjunction with television camera as a recording medium.

The concept of replacing the photographic emulsion by video recording and display occurred to several independent groups simultaneously. Macovski [3] in USA, Schwomma [14] in Austria, Köpf [14] in West Germany, and the Lougborough group in England, headed by Butters and Leendertz [2]. The first three groups considered the system to be a pure extension of holographic interferometry techniques. The last group, being very active in the emerging laser speckle research at that time, considered it more as speckle techniques and introduced the name ESP - Electronic Speckle Pattern Interferometry - for the techniques. However, the distinction between speckle and holographic methods in not always apparent when television systems are used. Unfortunately, the main problem encountered in most investigation was the low-resolution capabilities of photo-cathodes in comparison with the resolution capabilities of photographic emulsions. However, digital holography utilizes all the advantages of the CCD camera. Fast acquisition of the primary holograms, rapid digital storage, and numerical evaluation instead of optical reconstruction, thus not suffering from optical imperfections or limited diffraction efficiency.

The CCD camera that has been used in this project is low resolution and it limits the size of the objects to be recorded and requires a long distance between the object and CCD-target. However, it still can produce good holograms in this limited range.