# Chapter 1

## Introduction

There are many new challenges in measurement techniques, introduced by the shape and structure of the test objects that require development of reliable advanced measurement and testing methods. Generally measurements methods are being categorized into two types that is non-destructive (non-contact) and conventional contact methods used for measuring the object's dimension. Both types of method have their own advantages and disadvantages [1.1]. For example, non-destructive and non-contact methods such as using laser beams need more complicated set-up and might be harmful to living objects, but their accuracy could be higher and more reliable and the method could not be ignored. In contrast, contact methods do not need complicated equipments for active energy sources (which might be expensive in cost), but the accuracy may not be as good as that of some laser based methods in some aspects [1.2].

Surfaces with steep edges and varying shapes properties are usually not measurable with conventional methods of measurement and some delicate samples with shape varying in time especially in the field of biology require non-contact and non-destructive techniques for measuring. Moreover, the optical methods are relatively unaffected by irregularities of the samples surfaces and were able to detect small changes in nanometer range, which cannot be detected using the conventional contact methods. In optical metrology, light is used for measurements, by recording the light transmitted or reflected from an object [1.3]. This measurement could be of obtaining the magnitude of a quantity such as: height of the object, deformation to the object of interest, stress, refractive index profile, temperature distributions, aberrations in optical system etc. Measurement is very important because it allows us to understand the dimensions, the profile and in general it gives the overview of an object. For this reason we need methods which are capable of measuring various parameters of the object accurately and analysing it's characteristics under different parameters.

Dynamic characterization of the phase objects is a challenging task since most phase objects such as biological [1.4] samples like cells [1.5] are mostly transparent to electromagnetic radiation in the visible regime. But the imaging and visualisation of phase objects is very important especially in medical field [1.4, 1.5]. Direct imaging of phase objects, like living cells, refractive index distributions in transparent object etc., is difficult because they do not produce appreciable variation to the amplitude of the wavefront interacting with them, but they introduce a change in optical path length, hence phase of this wavefront. Phase objects could be characterized by measuring the phase changes occurring to this wavefront [1.6, 1.7]. Refractive index distribution existing inside such an object produces a spatial variation in the phase of the wavefront passing through the object [1.8]. The refractive index in turn depends upon many local parameters such as inhomogenity, density, temperature, impurity distribution etc. So a measurement of the refractive index distribution could be used to map these parameters. As mentioned these types of phase objects include gaseous systems, temperature distributions produced by flames, plasmas, biological specimens etc. The measurement and mapping of these parameters with fine spatial and temporal resolution is of primary interest to any one working in these fields.

A variety of optical measurements have been already proposed for example optical interferometry is used for this phase measurement. There are several interferometric methods for density distribution measurement of gaseous systems. Holography is one interferometric technique which can be used to reconstruct the whole field (amplitude and phase) of the wavefront interacting with the object. Holography technique can be used for 3D measurement of object's size [1.9].

## 1.2 Holography

It is well known that the main purpose of holography is recording and reconstruction of optical wavefront of a scene in a hologram [1.10]. Hologram is a Latin word made from two words, holos and gram which mean whole and recording (written) [1.11]. Hologram records the complex amplitude of a beam coming from an object rather than the intensity distribution in the image, which is contrast to the case in photography [1.11]. Thus holograms are nothing but micro-interference patterns obtained as results of superposition of waves (wavefront) that is object wave and the reference wave. Both reference wave field and a signal wave field should be of the same wavelength. Looking at hologram it creates the illusion that makes the object appear as real and as if it is there inside the hologram. To reconstruct the hologram optically, a reference beam is made to illuminate the hologram (on the photographic plate) to see the object again. Moreover, a hologram contains a codified data which contain amplitude and phase of the optical wave. When recording the hologram the phase information of wavefront gets preserved [1.13]. This information is used to determine the appearance of an object such as three-dimensional scene (3D effects) that is the depth of an object which is not there in photograph [1.14].

The ideas behind holography were first invented by Dennis Gabor in 1947. By then it was known as wavefront reconstruction in the field of electron microscopy [1.15]. He was trying to remove aberration issues in order to improve the resolution of electron microscopes. Gabor made up the term hologram which contained all information about the object's wavefront, i.e. both the amplitude and the phase. Lacking a proper coherent light source, the interest for holography seemed to be washed out until the invention of the laser by Dr. T.H. Maiman in 1960. The monochromatic (one wavelength) and coherent (light in phase) output from the laser made it possible to produce distortion free holograms of high quality. New techniques and fields of applications were discovered. Improved laser and film technology have made the technique generally available for research.

Holography has been used as tool in optical metrology technology since it is capable of reproducing the whole light field [1.16]. In addition it can used to compare the object wavefront with a known reference wavefront for the measurement at the micro level range.

## 1.3 Conventional holography

Conventional holography requires a real object to be illuminated using actual lasers. The recording of the complex amplitude is accomplished by setting up interferometry in the lab. Therefore, a reference wave is added to the object wave at the recording plane. This happen when object wavefront is interfered with a known reference wavefront, as a result of this interferogram is recorded on a photo-sensitive medium [1.14]. As in any interferometric experiment, care must be taken to ensure that the total optical path difference between both beams is not larger than the coherence length of the laser being used.

### 1.3.1 Recording materials

It is customary to use photographic plates as media to store the record of the interferogram [1.14]. This requires a wet processing as well as the placement of the photographic place exactly at the initial position. The photographic plates are not recyclable also. In essence holographic plates differ from photographic film only in that the former are capable of storing information at much higher spatial densities or resolution than the latter. A typical spatial resolution for photographic film is 90 lines per mm lines (l/pm), whereas for plates this value ranges from 1000 to 5000 l/pm. Any photo-sensitive medium can be used to record holograms and some of the other hologram recording mediums are given in Table 1.1. The holograms can be recorded as either an amplitude pattern (change in colour of the recording medium) or as a phase pattern (change in refractive index of the recording medium) giving rise to amplitude and phase holograms respectively.

Table 1.1: Hologram recording mediums

| Recording material | Type of hologram |
|---|---|
| Photographic plates | Amplitude/Phase hologram |
| Dichromated Gelatin | Phase hologram |
| Photoresist | Phase hologram |
| Photothermoplastics | Phase hologram |
| Photopolymers | Phase hologram |
| Photochromics | Amplitude holograms |
| Photorefractives | Phase hologram |
| Semiconductors | Amplitude holograms |

## 1.4 Electronic recording devices

As seen any photo-sensitive medium can be used for recording holograms and so the recording using electronic devices such as semiconductor arrays is possible. Light sensitive photo-detectors can be used to record holograms instead of photographic plates [1.14]. Charged Coupled Devices (CCD) and Complementary Metal-Oxide Semiconductor (CMOS) sensors are light sensitive devices which are capable of recording holograms. Normally the size of the CCD sensor is 5-10 mm with pixel sizes in the micrometer range [1.17].

## 1.5 Computer-generated hologram

A Computer Generated Hologram (CGH) image is a hologram computed by numerically simulating the physical phenomena of light diffraction and interference [1.18-1.20]. That is computing the interference pattern between an imaginary object wave and a reference wave [1.21]. The CGH can be then launched onto the SLM device and using an expanded laser beam one can then illuminate the SLM and to reconstruct the 3D image through light diffraction theory [1.22].

## 1.6 Digital Holography

Digital holography is the state of the art holographic technique, which uses optical recording and numerical reconstruction and this thesis describes the efforts to develop digital holography techniques in optical metrology that are capable of imaging and measuring a wide range of object parameters. Holography is a method for recording and reconstructing the amplitude and phase of a wave field and basically a hologram is a recording of the micro-interference pattern produced by the wave field passing through or scattered by the object under study (object or signal beam) and a coherent background radiation (reference beam, usually a plane wave front) [1.23]. Holography is a widely used technique for recording and reconstructing three-dimensional (3D) information of an object. In classical holography, photographic films are used to record holographic patterns and the reconstruction is performed optically [1.14]. Recent advances in charge-coupled device (CCD) and computer technology have permitted replacing photographic films with semiconductor arrays containing large number of small sized detectors and optical reconstruction with computer-driven numerical reconstructions [1.16]. Digital holography is thus referred to, as the technique that uses a CCD camera to record holographic patterns and performs the reconstruction numerically using a computer. In comparison with classical optical holography, digital holography has the major advantage because it eliminates the need of wet chemical development processing and mechanical focusing and, thus, leading a much faster and flexible holographic processing. In addition, both the intensity and phase of the object can be retrieved from digital holograms and accordingly, digital holography has been successfully applied in 3D information processing [1.17, 1.18].

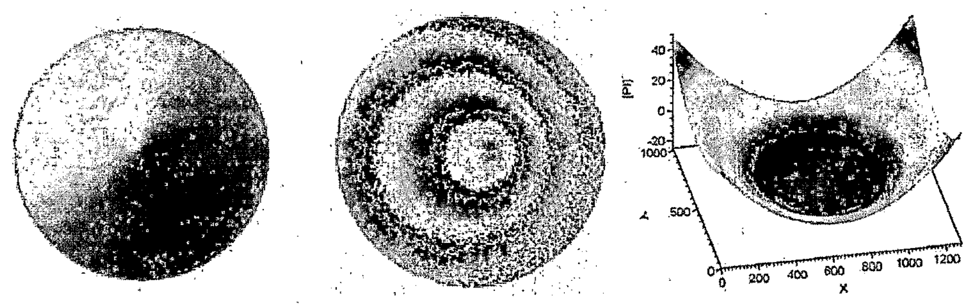
As mentioned the main advantage of digital holography is that, due to the numerical reconstruction procedure one can obtain the phase of the wave field directly without using the phase stepping techniques which is normally associated with phase recovery in conventional holography and interferometry. Digital holography finds many applications and one of its main applications is holographic interferometry, which makes it possible to compare wave fronts existing at different times in the computer. The uses of digital holography range from deformation and shape measurement to microscopy. Another aspect of digital holography being investigated is its use in determination of the state of wavefronts for testing of optical components like lenses. The state of the wavefront at different lens positions could be used to determine different lens parameters like its focal length, radius of curvature, as well as amount of defocusing. This makes digital holography a versatile technique which provides non destructive and non-contact techniques of testing, measurements and analysis.

There are several other innovative digital interferometric techniques capable of micro range measurements, such as digital speckles patterns, phase shifting interferometry, moiré interferometry methods, tomography, Fringe projection, moire, digital shearography etc [1.24, 1.25]. These techniques have merits and some also demerits. In the above techniques, no single technique or method is fully suitable because of many reasons or drawbacks in optical metrology. Each method presents some limitations. There are, however, some distinct disadvantages to some of these techniques.

Digital Holography is a very sensitive tool for wave font sensing. The phase and amplitude of the test wavefront is recorded by combining (interfering) it with a known background or reference wave [1.26]. The object wavefront is reconstructed by making the reference beam impinge on the developed hologram [1.19]. The principal purpose of wavefront detection or sensing is to determine and characterize the deviation of the test wavefront from ideal wavefront. The wavefront is a surface of constant optical path length from a common source. Many wavefront sensing techniques have been proposed which are used to estimate optical systems distortion like Shack-Hartmann sensor, pyramid, geometric and the curvature wavefront sensors etc [1.10]. In the Shack-Hartmann and pyramid wavefront sensor, a strong duality in the imaging and aperture planes exist allowing comparison of the performance of the two wavefront sensors which is time consuming. Both sensors subdivide the input wavefront into smaller regions and measure the local slope. However, this makes the system become more complicated. The geometric wavefront sensor can be considered to be an improved curvature wavefront sensor as it uses a more accurate algorithm based on geometric optics to estimate the wavefront. The algorithm is relatively new and has not found application in optics systems. Shack-Hartmann Sensor, which determines the wavefront phase by dividing the incoming test beam into sub-beams using a lenslet array. The phase is determined from where the focal spot from each lenslet component is formed. But due to the use of the lenslet array, with each component having a diameter in the range of some 100μ, it lacks lateral resolution.

Unlike shack-Hartmann wavefront sensor digital holography directly provides the phase reconstructions and hence wavefront profile with high lateral resolution, making it an ideal tool for this purpose [1.11-1.17].

Some of the advantages of digital holographic technique are based on the fact that: The reconstructed wavefronts can be compared directly with a synthetic wavefront generated in the PC. The wave field profile, i.e. the amplitude and phase distribution of the wavefronts, can be specified on the plane where the best reliability is desired. The phase is known of carrying all information about the object. The field is back-propagated to the hologram with the use of the Fresnel Kirchhoff's integral and Angular spectrum propagation [1.26]. The recorded hologram structure is capable of converting the incident field into the desired output. As an example Fig. 1.1 shows the recorded hologram and the corresponding recosntructed phase distribution providing a complete 3D profile of the object.




(a) (b) (c)

Fig. 1.1: Shows a concave aluminium object: (a) Digital hologram recorded by using a CCD camera, (b) reconstructed phase-contrast image, (c) three-dimensional image.

Moreover, because of fast algorithms currently existing, the numerical reconstruction methods are capable of reconstructing arbitrary 3D images and this have brought a lot of researchers to work on this field. So there clearly remains enormous potential associated with extended range of optical measurement to be explored sooner or later.

### 1.6.1 Applications of digital holography

Digital holography involves recording and reconstruction process is then performed numerically giving quantitative information of the amplitude and phase of the wave front. This offers new possibilities for a variety of applications ranging from deformation measurement to phase contract microscopy. It has wide ranging applications including shape and deformation measurement, imaging of refractive index distributions and microscopy [1.27-1.35]

## 1.7 Thesis Objectives

The main objective of this thesis is the development of measuring techniques capable for measuring a wide range of samples. This is addressed from the perspective such as accuracy requirements of the methods, applicability of the technique to a wide range of applications, and friendly ease of use of the methods. There is an ever increasing demand on non-contact techniques for measuring in industries, medical area and also in research field. This growing demand for noncontact measurements has already led to the development of 3D imaging methods such as conventional holography. Holography is a very sensitive tool for wavefont sensing. We addresses the applications of the use of digital holographic interferometry for measuring the phase of the object wavefront directly from the reconstructed complex amplitude, such application include phase retrieval. To investigate the development of digital holography techniques in optical metrology system for measurement and monitoring various parameters such as temperature distribution and refractive index to characterise optical properties of phase object materials. Another aim of this work was to develop virtual displacement measurement methods in the field of digital holography, which require only simple and known optical setups. A future aim is to apply, improve and investigate digital holographic interferometry for particle size measurement

### 1.7.1 Thesis Outline

The structure of the thesis is as follows:

Chapter 1: Presents a brief introduction to this thesis and the research project of which it is a part. The chapter introduces the basic background of holography and the some concepts of digital holography. A summary of the previous work done as part of this research project is also presented.

The first part of Chapter 2 summarises the basic knowledge about holography and digital principles in optical metrology. Investigation into the fundamental digital holography for optical metrology theory relevant to the understanding of this thesis, recording and numerical reconstruction of complex amplitude and phase are described. Contemporary techniques used in digital holography for optical measurement have been discussed and the reasoning behind the selection of the technique is explained. We give mathematical foundations and applications to hologram recording and reconstructions.

Chapter 3 gives a brief introduction to aberrations in an optical system and analyzing them using digital holography techniques. Aberrations are present in most optical imaging systems such as lenses. They are generally a consequence of the fabrication process. Using the concept of wavefront, the effects of reflection and refraction, in changing the direction of light can be described as modifications to the wavefront. After the introduction the use of digital holography in finding various parameters of the wavefront as well as the optical element producing this wavefront is described.

Chapter 4 begins with an explanation of the temperature distribution and refractive index profiling involved in of the analysis of optical characteristics of phase object like glass and candle flame. In this case, the digital holography has been utilized to evaluate the heat mapping inside toughen glass, due to the thermal variations refractive index is calculated.

Chapter 5, Holography technique can be used for 3D measurement of particle size and its topology. The direct measurement of the three-dimensional micro particles is of great interest to medical research as it is able to reveal the complete topology of uneven structures. The power of digital holography is well-appreciated as a size and shape measuring tool. Since digital holography can reconstruct the phase distribution, it is an attractive tool for detection, measurement and characterization of micro-objects.

Chapter 6 summaries the work and proposes future work which can be done using digital holography.

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