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**LENSSLESS IN-LINE DIGITAL HOLOGRAPHY FOR
DYNAMIC APPLICATIONS**

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SCHOOL OF MECHANICAL AND AEROSPACE
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LENSLESS IN-LINE DIGITAL HOLOGRAPHY FOR DYNAMIC APPLICATIONS

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SUMMARY

Digital holography (DH), as a tool of optical metrology, is able to address the challenges of recent requirements from technological developments. The aim of the present work is to develop digital dynamic holography as a metrological tool for both transmission and reflection applications. A lensless in-line digital holographic microscopy system is proposed and its performance for dynamic 3D imaging and micro-measurements is presented in this thesis.

The literature review on digital holography suggests this to be a rapidly growing field. Various digital recording and reconstruction methodologies have been proposed along with applications in micro and bio engineering. The off-axis DH system presents certain restrictions compare to in-line system, such as partial use of the CCD sensor, poor imaging resolution, and the requirement for higher spatial resolution for the CCD. To address these limitations and to provide solution for the recent requirements of dynamic optical metrology, a lensless in-line DH system for dynamic 3D imaging and micro-measurement is proposed.

The information recording capabilities of an in-line based DH system is presented first. Exploiting the advantages of the in-line system, a lensless in-line digital holographic microscope (LDHM) is presented for reflection and transmission applications. The methodology for magnification in the LDHM system using a diverging reference wave,

and its retrieval algorithm using a converging reconstruction wave, is proposed and verified.

The first dynamic application to which this system is applied is for 3D visualization and tracking of micro-particles. The LDHM system is explored for micro-particle analysis and shows how to resolve the problems of poor lateral and depth resolution associated with using a collimated wave. The methodologies for dynamic analysis of micro-particles (size $9.6\mu m$) in 3D, based on hologram addition and intensity threshold method, are developed.

Then, time-averaged in-line digital holography is explored for vibration analysis. A double exposure method is developed for the simultaneous study of the vibration modes and mean-static deformation during a vibration cycle. The subtraction of two numerically reconstructed digital holograms recorded at the same resonant frequency but with a small difference in amplitude shows the mixing of Bessel type time average fringes due to vibration and the double exposure fringes due to difference in the mean deformation of the object. It is shown that separation of these fringe patterns can be readily accomplished numerically. The effect of variation in the recording distance on the reconstructed amplitude and phase information for lensless magnification is studied. The sampling of hologram fringes and of individual speckles is independently studied and their effects during the reconstruction process are presented.

To demonstrate the applications of the reflection LDHM system, the vibration characterization a MEMS diaphragm is presented. It is demonstrated that subtraction of the phase information of holograms recorded at the vibration state and reference state shows the cluster of the time-averaged and mean deformation fringes. Furthermore, vibration characterization of MEMS cantilevers is presented. Thermal deformation of a MEMS micro-heater is analyzed based on the principle of the phase subtraction corresponding to different thermal deformation states.

LIST OF SYMBOLS

d - Hologram recording distance

$M \times N$ - Number of pixels of CCD array

$\Delta\xi \times \Delta\eta$ - CCD pixel size

(α, β) - fill factors of CCD

$\otimes$ - Two dimensional convolution

(x, y) - Object plane coordinates

(ξ, η) - Hologram plane

(x', y') - Reconstructed image plane

$\Delta x' \times \Delta y'$ - Reconstructed image pixel size

d' - Reconstructed distance

λ - Wavelength of light used

k - Wave vector

$\mathfrak{F}$ - Fourier transform

$\mathfrak{F}^{-1}$ - Inverse Fourier transform

S_o - Object size

S_s - CCD sensor size

θ - Interference angle

Δ - Fringe spacing

O - Object wave

R - Reference wave

H - Hologram

r - Spatial distance during diffraction process

I_o - Intensity of the object wave

I_R - Intensity of reference wave

ν - Spatial frequency of hologram fringes

Ω - Speckle size

f_s - Spatial frequency of speckles

(ζ, χ) - Spatial frequency presented in the hologram

$f_\xi \times f_\eta$ - Area of spectral domain

$S_\xi \times S_\eta$ - Spatial dimension

S_f - Spectral bandwidth product

δ - Angle of diffraction

γ_o - Spatial frequency of object

D - Pinhole to CCD distance

l - Pinhole to object distance

I - Numerically reconstructed intensity

ϕ - Numerically reconstructed phase

U - Reconstructed wave

g - Impulse response of the coherent optical system

G - Transfer function of free space propagation

Δz - Depth of focus

A_o - Amplitude of the object wave

$\vec{k}$ - Propagation vector

$\vec{K}$ - Sensitivity vector

$\vec{d}$ - Displacement vector

M_T - Characteristic function

J_0 - Zero-order Bessel function

$\Delta\phi$ - Phase difference

$\vec{z}$ - Vibration displacement

ω - Angular frequency of vibration

g' - Geometrical factor of optical system

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CHAPTER 1

INTRODUCTION

1.1 Background and motivation

1.1.1 Optical metrology and dynamic measurements

An optical wave is characterized by its amplitude, frequency, phase, polarisation, and direction of propagation. When a coherent optical wave is incident on any object, the reflected and/or the transmitted waves contain information about the optical and physical properties of that object. The amplitude contains information about reflectance or attenuation of the object, while the phase gives topography or thickness characteristics. Thus, both these parameters are important for complete 3D study of objects. Optical metrology has many advantages over other measurement techniques because of its non-invasive, high sensitivity, large temporal and spatial resolution features.

Various optical methods are being used for imaging and measurement applications. The miniaturization of the object size puts new challenges for optical metrology. Some examples are dynamic microscopic imaging (e.g. micro-particles image velocimetry, micro-fluids flow analysis, and the study of biological samples), and measurement on micro-structures (MEMS/MOEMS devices). The requirements are better measurement system performance for full 3D, large field of view and high imaging resolution as well as real time analysis.

1.1.2 Holography

Holography is an important tool for optical metrology. Dennis Gabor invented holography in 1948 [1, 2] as a two-step lensless imaging process for wavefront reconstruction. The phase, amplitude, polarization, and coherence of a wave field can be stored in a hologram during recording. Since these quantities cannot be measured directly with conventional detectors, which are only sensitive to the intensity, this makes holographic technique most attractive. Holography is well established for scientific and engineering studies and has found a wide range of applications. As a tool of dynamic imaging and measurement, holography has several advantages and can be explained as follows:

❑ Full field 3D information storage

A single hologram has the capability to store the full field 3D information. Thus holography provides the whole spatial location of the object during reconstruction process. On the other hand, holographic interferometry provides the full field deformation measurements of objects [3].

❑ Non-destructive method

Holographic methods have been applied for non-destructive testing of objects [3]. Laser light illuminates objects and the scattered light is used for imaging and measurement applications. The intensity level of light does not cause any damage to the sample and thus provides the non-invasive and non-contact measurements.

❑ Higher imaging resolution and measurement accuracy

Holographic microscopy can achieve diffraction limited resolution [4]. The resolution has been significantly improved by using shorter wavelength light sources. Also holographic interferometry provides higher accuracy for deformation measurements [3].

❑ No need of special sample preparation

Holographic methods can be performed with diffusely reflecting surfaces, and thus suitable for applications in industrial environment. There is no requirement for special sample preparation, this features is significantly important for the study of micro-objects.

❑ Static and Dynamic imaging and measurement capabilities

By selecting suitable recording materials, holographic methods are successfully applied for both static as well as dynamic imaging application. Multiple exposure, real time, and pulse holographic interferometry has been used for dynamic metrology [5, 6]. Time averaged holographic interferometry on the other hand is used for vibration measurements [7].

In classical holography, photographic plates or thermoplastic films are used to record holograms in vibration free environment and then optically reconstructed. The handling of these materials is time consuming and the vibration isolation requirement makes holographic technique less popular to implement in industrial environment. In addition when smaller size objects are studied, the complicated experimental set-up and evaluation processes during reconstruction often impose challenging problems.

1.1.3 Digital holography

With the recent development of digital computers and Charged Coupled Devices (CCD), digital holography was proposed [8, 9] to overcome the problems of classical holography. Digital recording devices (CCD sensor) provide flexibility to record holograms directly in digital form. The reconstruction process is then performed numerically giving quantitative analysis of amplitude and phase of the wavefront. This offers new possibilities for a variety of applications, which in classical holography was done only qualitatively.

There are two types of digital holography: in the first, a hologram can be generated in the computer by digital simulation of the interference of the object and reference beams. These have been used in the development of Holographic Optical Elements (HOEs). In this case, since the result of the Computer Generated Holograms (CGH) need to be evaluated rapidly, optical reconstruction using Spatial Light Modulators (SLM) have been explored [10]. In the second type, optically generated hologram is recorded digitally by using a CCD. These digital holograms are then reconstructed numerically by the simulation of the reconstruction process with the help of computers. In the present study, Digital Holography refers to the latter type.

CCD sensors as holographic recording medium allow recording of holograms at video rates and are in a format readily available for numerical reconstruction. The computer reconstruction process is very flexible and can be used in a variety of ways to focus the

image at different planes or removal of background etc. Thus, in-comparison to conventional optical holography, digital holography has the following advantages:

- ❑ Cumbersome wet chemical processing, which is time consuming and costly, is not needed.
- ❑ Vibration isolation is not needed in digital holography during the recording process because the available CCD sensors have much higher sensitivity within the working wavelength range than the photographic films.
- ❑ Recording of holograms are possible in digital forms at video rates and the data is available for numerical reconstruction.
- ❑ Quantitative phase and amplitude information can be directly calculated during numerical reconstruction process. Direct phase determination is most useful in interferometry and phase-contrast imaging.
- ❑ Whole object wave field can be reconstructed for real time measurement without the problem of exact repositioning of hologram as in conventional holography.

Digital holography is an exciting new method for handling of light. The capability of whole field information storage in holography and the use of computer technology for fast data processing open a lot of possibilities to develop digital holography as a dynamic

metrological tool. As a noble method, digital holography has received increased attention and has been developed for various applications in the last few years. Digital holography has the potential to address recent challenges for optical metrology brought about by miniaturization, new material and processes.

Digital recording of hologram, using CCD sensors, requires to fulfill the sampling theorem across the entire sensing area. Commercially available CCD sensors have the limitations such as low pixel resolution and smaller sensing area. Off-axis digital holography system utilizes only partial area of CCD sensor and provides poor imaging resolution. In contrast, the in-line system helps to relax the spatial resolution requirement on CCD sensors and utilize the full sensing area. In-line based geometry significantly improves the performance of digital holography system and shows higher imaging resolution and larger field of view. Methodologies based on in-line digital holography have been explored for imaging and measurements. However, they are mainly limited for static applications. Further extension of possible application areas of in-line based system is extremely important to fully exploit the capabilities of digital dynamic holography.

1.2 Objectives and scope

The main objectives to be achieved in this research include:

1. To investigate the capabilities and methodology of in-line dynamic digital holographic system for imaging and measurement application. The incorporation of

lensless magnification, with in-line digital holographic system is developed for both transmission and reflection.

2. Applications of the developed transmission system for 3D micro-particles imaging, and development of methodology for their dynamic analysis.
3. To develop the methodology for vibration analysis using reflection based set-up. The experimental investigations for dynamic and vibration characterization of membranes and MEMS devices.

The following important research scopes are covered to achieve the proposed objectives:

- ❑ Studying the theory of digital holography and optimize the recording and reconstruction methodology for in-line digital holographic set-up.
- ❑ A Lensless in-line digital holographic microscope (LDHM) is proposed. The system capabilities are analyzed. A new methodology is developed for controlling the reconstruction parameters, which is suitable for both transmission and reflection based systems.
- ❑ Micro-particles imaging in 3D is experimentally investigated using transmission set-up. The methodologies for dynamic 3D analysis are explored and experimentally presented.

- ❑ Methodology of time-averaged in-line digital holography is developed for vibration analysis. The study of the effects on the reconstruction parameters for lensless reflection microscopic system is presented and experimentally investigated.

- ❑ Vibration characterization of MEMS devices are experimentally investigated using the developed reflection set-up. The capabilities of the system are thus explored for dynamic characterization of MEMS devices.

1.3 Organization of the thesis

In Chapter 2, the literature review is presented. It explains the optical methods used for imaging and measurement applications and also discusses their limitations. The development of digital holographic methodology is also presented. Here procedure of digital recording of holograms and numerical reconstruction methods are presented. The applications of digital holography presented so far are explored. Development with in-line based system and their applications are reviewed. The critical analysis of the methodology is given, followed by project proposal of in-line based lensless microscopic system.

Chapter 3 explains the optimization of the recording and presents the reconstruction methods for in-line digital holography. The analysis of lensless microscopic system is presented for transmission and reflection geometry. The methodology for controlling the reconstruction parameters is also discussed.

The studies of 3D micro-particles imaging are presented in chapter 4. The imaging mechanism and measurements methods for particles depth and size are presented. A new method for slicing of amplitude images is explained for analyzing particles in different planes and is experimentally demonstrated. The limitations of the collimating wave digital particle holography are discussed and advancements with lensless digital holographic microscopy are given. Also the methods for dynamic 3D analysis are also presented.

In chapter 5, methodology of time-averaged in-line digital holography is presented for vibration analysis of membranes. A double exposure method is developed for the study of vibration mode and mean static deformation analysis. It is useful to suppress the background noise caused by in-line geometry. Furthermore, the sensitivities on reconstructed amplitude and phase information from time-averaged holograms are studied with magnification for the lensless microscopy system.

In chapter 6, the vibration characterization of MEMS diaphragm and dynamic thermal deformation analysis in MEMS micro-heater are presented. The vibration modes corresponding to different resonant frequencies are analyzed. The behavior of the vibrations is studied for different excitation conditions to the object. Furthermore the vibration analysis of cantilevers is explored using lensless reflection microscopy system.

Chapter 7 gives the conclusions of the findings of the research works followed by directions for future work.

CHAPTER 2

LITERATURE REVIEW

In this chapter, the review of optical imaging and measurement techniques is discussed. The advantages of holographic method over other existing methods are presented, which is followed by the development of digital holographic methodology. Current research status of digital holography for applications in imaging and measurement is presented. Advantages of in-line digital holographic over off-axis system are discussed and a novel system based on lensless in-line microscopic geometry is proposed for dynamic applications.

2.1 Imaging and measurement schemes

Optical measurement techniques offer significant advantages over their counterparts for imaging and measurement applications. Remote analysis, non-contact measurement, whole field visualization, and no need for special sample preparation are the major features. Increasing possibilities of computer-aided data processing have led to a new revival in optical metrology.

Recent technological development and miniaturization of the test objects create new challenges for optical metrology e.g. to provide convenient tool for whole field imaging and micro-systems characterization, and to provide experimental data for computer aided engineering for fast and accurate measurements etc. The recent requirements can be summarized as follows:

- Information delivery in 3-D (x, y, z) , (x, y, t) and 4-D (x, y, z, t)
- Active interferometer integration with microscopes
- High accuracy in large field of view
- Gathering data in-situ and real time analysis

Figure 2.1. Methods of optical metrology

Different optical methods are used for these measurements depending to the requirements. These methods can be divided into two broad categories, called imaging and interferometric methods, summarized in Figure 2.1.

2.1.1 Optical methods for microscopic imaging

Microscopic imaging is a technique for producing visible images and details of the smaller size objects. These techniques are basically divided into three main branches; optical [11], electron [12], and scanning probe microscopy [13].

Optical microscopic techniques involve the principles of reflection, refraction, or diffraction of the light incident on the objects. The subsequent collection of the scattered light forms the microscopic image. The imaging process is carried out either by full field method (e.g. conventional optical microscopy) or by scanning the beam over the sample (e.g. near field scanning optical microscope [14] and confocal microscopy [15]).

(i) Optical microscopy

An optical microscopic image is formed by passing visible light reflected or transmitted from the object through lenses. The microscope contains a single lens, or a system of lenses and imaging equipment along with a light source [11].

Conventional optical microscopic methods (Figure 2.2(a)) are based on amplitude contrast imaging and thus show only the change in the contrast of light absorbed or reflected by the sample. Alternatively in phase contrast microscopic method [16] the

changes in refractive index appear as difference in contrast of the microscopic image (Figure 2.2(b)). Phase contrast microscopic imaging uses spatial filtering technique and the observed intensity is linearly related to the phase shift introduced by the object. Interference occurs between the phase shifted direct light and diffracted light, and results in a phase contrast image.

The differential interference contrast microscopic system (Figure 2.2 (c)) is also used to study the difference in the optical densities [17]. The optical system consists of a Nomarski or Wollaston prism, which splits the light into an ordinary beam and an extraordinary beam. The polarized beams are passed through the specimen and then recombined by the similar prism. A differential interference contrast image is formed which represents the phase changes occurred in the path of light beam created by the specimen.

Figure 2.2. Optical system geometries of (a) Optical microscope, (b) Phase contrast microscopy, and (c) Differential interference contrast microscope

(ii) Near field scanning optical microscopy

In near field scanning optical microscopy a sub-wavelength size aperture source is used as a scanning probe to study the object with high resolution ($\sim 50\text{nm}$). The light passes through a small pin-hole (sub wavelength diameter) and scans the sample which is placed in near field (less than the wavelength of light) [14] as shown in Figure 2.3. By illuminating the sample with the near field of a small light source, optical images are obtained with resolution beyond the usual diffraction limit. The spatial resolution depends on the size of the pin-hole. Thus, this kind of arrangement improves the spatial resolution of the conventional optical microscope which is diffraction limited.

Figure 2.3. Principle of near field optical scanning microscope

(iii) Confocal microscopy

Confocal microscopic system is a point-by-point imaging method which provides the 3D reconstruction of the objects [15]. It uses a point illumination and a pinhole in an optically conjugate plane. The set-up geometry is shown in Figure 2.4. A laser beam, after passing through an aperture, is focused at a tiny spot (ideally diffraction limited) by a microscopic objective and incident onto the sample. The reflected light is then recollected by the same objective lens and focussed to a pinhole and detected by the photo detector. The detector only detects the light which is coming from the pinhole, and thus out-of-focus point of the object is suppressed (shown by dotted lines). The thickness resolution of the system is defined by the numerical aperture of the microscopic objective lens. Since only one point is illuminated at a time on the sample, scanning over a regular raster is required for 2D or 3D imaging of the sample. The resolution of the system depends on the illuminating and creating detectable photons.

Figure 2.4. Principle of Confocal Microscopy

2.1.2 Optical methods for measurements

Optical methods based on interferometry are most commonly used for static and dynamic deformation measurements. For dynamic measurements, the amplitude and/or phase difference of the two patterns recorded at two different states provides dynamic changes. In case of vibration measurements, time averaged method is used to record behaviours of periodically vibrating objects. For time average recording the vibration frequency is much larger than the frequency of recording device. Laser based optical interferometry techniques provide high sensitivity, wide dynamic range and wide frequency response. These are non- contact type and allow measurement/ monitoring in hostile environment. Apart from frequency and amplitude measurement, the interferometry techniques can be used to measure absolute phase and map of relative phase.

(i) Classical laser interferometry

Classical laser interferometry is a well established technique for measurements [18, 19]. In it, the optical path difference between two waves occurs when the object is placed in the path of one wave. The measurements are performed with the sensitivity of a fraction of the illuminations wavelength. Additionally, by adding phase shifting and fringe processing techniques, the system capability can be improved for high-precision measurements. Recently, laser based classical interferometers are extended for the study of micro-scale objects for both static and dynamic measurements applications [20-23].

The well known classical interferometer is the Michelson Interferometer. By modifying its optical geometry, measurements of micro-sized objects for various kind deformations

of can be performed. The experimental arrangement of Michelson interferometer for measurements of smaller size objects and a typical fringe pattern are shown in Figure 2.5.

Figure 2.5. (a) Michelson interferometric arrangement for measurements, (b) Typical fringe pattern [18]

Limitations of classical interferometry:

- Point wise evaluation of the interference pattern is required on the surface of the object for measurements.
- Laser interferometry is limited to making measurements on highly polished surface of relatively simple object shapes.
- Phase shifting method is needed for getting modulo 2π pattern, it requires the precise control of reference mirror, and thus not suitable for dynamic measurements.

(ii) Moiré interferometry

Moiré patterns are formed by periodic structures of lines or strips of nearly the same periodicity. The most commonly used periodic structures are linear gratings [24]. Two-beam interference phenomenon has been extended to the realm of Moiré method for measurements with sub-micron level sensitivity [25]. High frequency phase gratings are transferred on the surface of the sample, moiré fringes are formed by the superposition of interference pattern of two beams and object grating. This kind of arrangement is well established for static/ dynamic measurements of in-plane displacements [26-29] and applied for electronic packaging and micro-mechanics [30-32]. Alongwith the development of electronics and optical components, a recently developed typical micro-moiré experimental arrangement system and in-plane measurement fringes are shown in Figure 2.6.

Figure 2.6. (a) Micro-moiré interferometric set-up, (b) In-plane measurements [27]

Limitations of the Moiré interferometry:

- Sample has to be prepared by replicating high frequency grating on the surface of the test object.

- The moiré fringes become fuzzy when objects of large curvature are examined.
- Since the sample surface needs to be prepared. It may effects the surface properties of sample and may results as an error in the measurement parameters, particularly when micro-size object under study.
- Although the technique has been demonstrated for both in-plane and out-of-plane measurements, but it is more suitable only for in-plane measurement.

(iii) Speckle Interferometry

Speckle pattern interferometry gives information about the displacement resolved in one direction, in-plane or out-of-plane [24, 33]. It is used for objects with optically rough surfaces and applied for both static and dynamic measurements. Two speckle interference patterns are recorded corresponding to two states of the object and the resulting correlation fringe represents the change during double exposure.

In the electronic detection using digital speckle pattern interferometry (DSPI), the two exposures are independently handled and their subtraction removes the DC component [34]. Phase shifting techniques can be easily incorporated with DSPI systems and hence deformation maps can be presented digitally. The availability of fast PCs and large-density CCD detectors makes the technique of electronic detection very attractive in metrology [35-38]. The schematic of a DSPI set-up and typical measurement fringes are shown in Figure 2.7.

Limitations of speckle interferometry:

- Poor image quality and low signal to noise ratio (SNR).
- Phase information is lost during speckle correlation process.
- The speckle size increases as the object size decreases. The measurement sensitivity decreases with increase in speckle size due to speckle correlation. Thus this technique is not suitable for deformation measurement of micro-size objects.

Figure 2.7 (a) Digital speckle pattern interferometric set-up, (b) Measurement fringes

[24]

(iv) Laser Doppler vibrometer

Laser Doppler vibrometer (LDV) works on the principle of laser interferometry [39]. The object beam is focused to a point on the moving object and reflected light is combined with a reference beam using a beam splitter. The light scattered from the vibrating object experiences a Doppler frequency shift which is proportional to the instantaneous velocity of the object in the direction of the laser beam. The frequency difference between the object beam and reference beam shows up as a light intensity modulation, which is

converted to an electrical signal by a photo detector. The Doppler frequency is independent of the direction of motion. In order to detect the direction of motion of the object, a Bragg cell is introduced in the reference beam for frequency shift [40].

Laser Doppler vibrometers are intended to make measurements on a single point of vibrating object. In order to determine model pattern of vibrating object it is necessary to scan the object over the surface. Practical implementation of this adds complexity in the optical arrangement and demands the vibration frequency is stationary over the time taken to complete the scan.

2.1.3 Holographic methods for imaging and measurements

Holography is a well established method of optical metrology for both imaging and measurement applications. It has several additional advantages over other conventional optical methods discussed so far.

Amplitude and phase are the two main information's used to characterize any optical wave. Optical detectors such as photographic films or CCDs can record only the amplitude, and the phase information is lost in this recording process. Holography, on the other hand, records both the amplitude and phase as proposed by Dennis Gabor [1-2]. When an object wave interferes with a known reference wave, the recorded interference pattern is called hologram. The information of the object wave is encoded in the interference pattern in terms of fringe modulation, location and spacing. The object wave can be reconstructed by illuminating the hologram with the same reference wave, as used

during the recording process. The first order diffracted wave from hologram is same as the object wave. Holography was successfully demonstrated, after the invention of lasers, by Leith and Upatniek [41-42] who used an off axis configuration to separate the object wave from the undiffracted wave.

The most attractive part in holography is recording of full 3D information about the object in a single hologram. This feature makes holography the best suited tool for imaging and measurement. A number of applications in microscopic imaging, interferometry, particles analysis, 3D display, colour imaging have been demonstrated [3, 43-44].

2.2 Digital holography

The major drawback of classical holography is the need for photographic plates, which involves wet chemical development process that is expensive and time-consuming. Also, vibration isolation requirement in holography is not compatible with industrial shop floor environments unless the pulsed lasers used. Moreover, the exact repositioning of the holograms for real time measurements, dependence of the reconstructed images & interference fringes on the optical system, and phase-shifting techniques makes classical holography a complicated process.

Use of digital recording of holograms would thus be a great advantage over the film based holography. Despite growth in CCD technology, the resolution of the best digital cameras are still about 50 times smaller than high resolution films used in holography.

However, the benefit of digital holography is numerical processing which provides the perfect solutions to the limited resolution of the recording system.

Hologram was first recorded digitally on an electro-optical device (vidicon) shown by Goodman [45]. Holograms in digital form were also obtained by sampling an optically enlarged part of a conventional hologram recorded on a photographic plate [46-47]. These digitized holograms were then processed numerically. The development of CCDs and their successful use in Electronic Speckle Pattern Interferometry (ESPI) [34-39] made an alternate way to record holograms directly in digital form. It enhances the flexibility and efficiency of the holographic methods, and thus provides newer qualities that are brought to optical information systems by digital computers and processors. Efficient numerical algorithms aided by fast processing speed, allows quantitative evaluation of holographic reconstruction for near real time applications.

The digital technology has made it possible for both recording and reconstruction of holograms by computers. The holography, where holograms are created by the numerical simulations and reconstructed optically, is called Computer Generated Holography (CGH) [10]. On the other hand, when an optical hologram recorded digitally by a CCD and reconstructed numerically, it is called Digital Holography (DH). The process of digital holography is shown in Figure 2.8.

Figure 2.8. Process of digital holography

The limited resolution of CCD cameras, used as a holographic recording medium, limits the maximum spatial frequency that can be recorded. The best commercially available CCD has a resolution of about 150 lines/mm ($6\mu\text{m}$), which is much poorer than the conventional holographic recording medium (silver halide emulsion ~ 5000 lines/mm ($0.2\mu\text{m}$)). This limited resolution restricts the angle between object and reference beams to few degrees only. To achieve good quality reconstruction, digital recording of holograms has to satisfy the requirements of Nyquist sampling theorem [48]. This implies that interference between two beams of wavelength λ intersecting at an angle θ gives fringe spacing $p = \lambda / \sin \theta$ and it must be larger than size of two pixels. For example, for a 3° interference angle between two beams of He-Ne laser ($\lambda = 0.6328\mu\text{m}$), the pixel size of CCD should be $6\mu\text{m}$ to fulfil the sampling theorem. This corresponds to the higher end of the CCD cameras. It is interesting to note that, it is the pixel size rather than the number of pixels of a CCD that is more important.

2.2.1 Digital holography development

The recording of holograms by CCD sensor and reconstruct the object wave by numerical methods is called Digital Holography [8]. It has received increased attention in the last few years. The main reason for this development has been the rapid improvements in storing and processing of digital information. The object wave can be numerically calculated directly from the holograms and this makes it possible to calculate quantitatively both the amplitude and phase information separately, which is not possible in conventional holography. These features make it a perfect method for both imaging and measurement.

(i) Recording of digital holograms

The diffraction region of the object wave, where the digital hologram is recorded, is used to classify the digital hologram. It is divided into two categories, Fresnel hologram and Fraunhofer hologram. The digital Fresnel holography set-up is shown in Figure 2.9. The interference of the reference beam and the object beam is recorded by a CCD sensor which is placed in the Fresnel diffraction region of the object wave. The collimated reference beam is incident normally on the CCD and θ is the offset angle of the object. Digital Fraunhofer holography is a special case of Fresnel type where object placed very large distance (infinity) from the CCD. The digital Fraunhofer holography configuration is shown in Figure 2.10, a lens is used to generate the far field diffraction pattern of the object wave. It was shown that the CCD can directly record off axis Fresnel's holograms, and real image was reconstructed by means of numerical methods [8].

Figure 2.9. Fresnel off-axis digital holography

Figure 2.10. Fraunhofer off-axis digital holography

Let (x, y) be the object plane and (ξ, η) be the hologram plane as shown in Figure 2.11.

The hologram, which is the interference of the object wave $O(\xi, \eta)$ and reference wave $R(\xi, \eta)$, can be written as

$$H(\xi, \eta) = |O(\xi, \eta) + R(\xi, \eta)|^2$$

$$H(\xi, \eta) = |O(\xi, \eta)|^2 + |R(\xi, \eta)|^2 + O^*(\xi, \eta)R(\xi, \eta) + O(\xi, \eta)R^*(\xi, \eta) \quad (2.1)$$

O^* and R^* are the complex conjugate of the O and R respectively.

The CCD, placed at the hologram plane, records this interference pattern. The recorded pattern is converted into a two-dimensional array of discrete signals by using the sampling theorem [48]. Let $M \times N$ be the total number of pixels of the CCD with corresponding size $\Delta\xi$ and $\Delta\eta$, then the digitally sampled holograms $H(m, n)$, can be written as [49]

$$H(m, n) = [H(\xi, \eta) \otimes \text{rect}(\frac{\xi}{\alpha\Delta\xi}, \frac{\eta}{\beta\Delta\eta})] \times \text{rect}(\frac{\xi}{M\Delta\xi}, \frac{\eta}{N\Delta\eta}) \text{comb}(\frac{\xi}{\Delta\xi}, \frac{\eta}{\Delta\eta}) \quad (2.2)$$

Where $\otimes$ represents the two-dimensional convolution and $(\alpha, \beta) \in [0,1]$ are the fill factors of the CCD pixels. Thus an optical hologram is sampled by each pixel over the entire array-off CCD sensor area, called digital hologram.

(ii) Numerical Reconstruction methods

The coordinate system of recording and reconstruction in digital holography is shown in Figure 2.11. Interference of object and reference beam is recorded at the hologram plane by the CCD sensor. The recorded hologram $H(\xi, \eta)$ is digitized by the sampling theorem as defined in Equation (2.2).

Figure 2.11. Coordinate system for digital holography

- Reconstruction by Fresnel transformation method

The reconstruction of hologram is a diffraction process. The diffraction geometry is shown in Figure 2.12.

Figure 2.12. Diffraction geometry of hologram reconstruction

The hologram $H(\xi, \eta)$ is illuminated by the reconstruction wave $R(\xi, \eta)$. The reconstructed wavefield at the image plane (x', y') at distance d' is given by the Huygens-Fresnel equation [48],

$$U(x', y') = \frac{d'}{i\lambda} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} H(\xi, \eta) R(\xi, \eta) \frac{\exp(ikr)}{r^2} d\xi d\eta \quad (2.6)$$

Where $k = \frac{2\pi}{\lambda}$, is the wave number and r is the distance between the points of hologram and image plane as shown in Figure 2.12.

Let r be defined by the Fresnel's approximation as,

$$r \approx d' \left[1 + \frac{1}{2} \left(\frac{x' - \xi}{d'} \right)^2 + \frac{1}{2} \left(\frac{y' - \eta}{d'} \right)^2 \right] \quad (2.7)$$

Then the reconstructed wavefield Equation (2.6) by using Equation (2.7) can be written as,

$$U(x', y') = \frac{e^{ikd'}}{i\lambda d'} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} H(\xi, \eta) R(\xi, \eta) \exp\left[\frac{i\pi}{\lambda d'} \{(x' - \xi)^2 + (y' - \eta)^2\}\right] d\xi d\eta \quad (2.8)$$

This equation is called the Fresnel approximation or Fresnel transform.

The impulse response $g(\xi, \eta)$ of the coherent optical system can be defined as

$$g(\xi, \eta) = \frac{e^{ikd'}}{i\lambda d'} \exp\left\{\frac{i\pi}{\lambda d'} (\xi^2 + \eta^2)\right\} \quad (2.9)$$

Using Equation (2.9), Equation (2.8) can also be written as

$$U(x', y') = e^{i\pi d'(\nu^2 + \mu^2)} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} H(\xi, \eta) R(\xi, \eta) g(\xi, \eta) \exp[-2\pi i\{\xi\nu + \eta\mu\}] d\xi d\eta \quad (2.10)$$

Here $\nu = \frac{x'}{\lambda d'}$ and $\mu = \frac{y'}{\lambda d'}$ are the spatial frequencies present in the hologram. Thus the reconstructed field is simply the Fourier transform of the product of the hologram, the reconstruction wave and the impulse response function [50]. i.e.

$$U(x', y') = \mathfrak{F}\{H(\xi, \eta) R(\xi, \eta) g(\xi, \eta)\} \quad (2.11)$$

Let $U(x', y')$ be the reconstructed wavefront behind the hologram. If the reconstructed wave is the complex conjugate of the reference wave, then a real image of the object wave is formed at the reconstruction distance d which is same as the recording distance of the hologram.

The image intensity can be calculated by the squaring the wavefield

$$I(x', y') = |U(x', y')|^2 \quad (2.12)$$

And the phase is calculated as

$$\varphi(x', y') = \arctan \frac{\text{Im}(U(x', y'))}{\text{Re}(U(x', y'))} \quad (2.13)$$

- Discrete Fresnel transformation

If the hologram recorded with CCD contains $M \times N$ pixels with pixel size $\Delta\xi$ and $\Delta\eta$ along the coordinates respectively. Then the reconstructed field defined by eqn. (2.10) converted to finite sums as [51]:

$$U(k, l) = \frac{e^{ikd'}}{i\lambda d'} e^{i\pi\lambda d' \left(\frac{k^2}{M^2 \Delta\xi^2} + \frac{l^2}{N^2 \Delta\eta^2} \right)} \times \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} H(m, n) R(m, n) e^{\left[\frac{i\pi}{\lambda d'} (m^2 \Delta\xi^2 + n^2 \Delta\eta^2) \right]} e^{\left[-2\pi i \left(\frac{mk}{M} + \frac{nl}{N} \right) \right]} \quad (2.14)$$

where $k = 0, 1, \dots, M-1$, $l = 0, 1, 2, \dots, N-1$. The Equation (2.14) is the discrete Fresnel transformation. The matrix $U(k, l)$ is the discrete Fourier transform of the product of $H(m, n)$, $R(m, n)$ and $\exp\{(i\pi/\lambda d')(m^2 \Delta\xi^2 + n^2 \Delta\eta^2)\}$. Thus calculation of reconstructed wavefield can be done effectively by using the fast Fourier transform (FFT) algorithm. The pixel size of the numerically reconstructed image varies with the reconstruction distance and is given by,

$$\Delta x' = \frac{\lambda d'}{M \Delta\xi}, \quad \Delta y' = \frac{\lambda d'}{N \Delta\eta} \quad (2.15)$$

Zero padding of the digital hologram has been proposed to overcome the effect of under sampling during recording process [52]. For this, holograms are fictitiously enlarged by padding zeros to increase the size.

- Reconstruction by convolution method

Reconstruction by convolution approach [53] is useful if the pitch of the reconstructed image has to be independent of the reconstruction distance. It can be shown that the diffraction integral (Equation (2.8)) becomes a convolution for a linear space invariant system [48]. Then the numerically reconstructed wavefield can be written as,

$$U(x', y') = [H(\xi, \eta)R(\xi, \eta)] \otimes [g(\xi, \eta)]$$

here, $\otimes$ indicates a two dimensional convolution. The reconstructed wavefield can be calculated by using the convolution theorem [48],

$$U(x', y') = \mathfrak{F}^{-1}[\mathfrak{F}\{H(\xi, \eta)R(\xi, \eta)\}\mathfrak{F}\{g(\xi, \eta)\}] \quad (2.16)$$

The calculation of the Fourier transforms can be performed effectively by the FFT algorithm. The Fourier transform of the impulse response is called the transfer function $G(n, m)$ of free space propagation and numerically defined as [51],

$$G(m, n) = \exp\left\{\frac{2\pi i d'}{\lambda} \sqrt{1 - \frac{\lambda^2 (n + N^2 \Delta \xi^2 / 2d' \lambda)^2}{N^2 \Delta \xi^2} - \frac{\lambda^2 (m + M^2 \Delta \eta^2 / 2d' \lambda)^2}{M^2 \Delta \eta^2}}\right\} \quad (2.17)$$

Then the reconstructed wavefield is given by,

$$U(x', y') = \mathfrak{F}^{-1}[\mathfrak{F}\{H(\xi, \eta)R(\xi, \eta)\} \cdot G(m, n)] \quad (2.18)$$

The pixel size of the reconstructed image by convolution method is same as the pixel size of CCD and does not vary with reconstruction distance, i.e. $\Delta x' = \Delta \xi$ and $\Delta y' = \Delta \eta$.

The Fresnel approach of reconstruction (Equation (2.11)) is fast and useful when the object is larger than the CCD, but variation of pixel size with reconstruction distance creates problems in application such as particles sizing and colour holography. The pixel size of the reconstructed image remains constant with reconstruction distance in convolution approach but it is used when the object size is smaller than the CCD. In case of large sized object, zero padding of holograms is necessary before reconstruction by convolution method [52].

Some additional developments in the numerical reconstruction method have been presented recently. Numerical reconstruction of holograms with variable viewing angles [54], non-diffractive reconstruction method [55], frequency analysis of digital holography [56-57], reconstruction of in-line holograms with Yang-Gu algorithm [58], reconstruction algorithm with adjustable magnification [59], controlling image size and parameters during reconstruction [60], reconstruction method for 3D shape measurement [61] have been proposed. Essentially, these have the same basics as the Fourier transform or convolution with some additional pre- or post-processing.

2.2.2 Current research status

- **Optical systems**

The poor resolution of the available CCD sensor imposes strong constraints on the angle between object and reference waves to few degrees to fulfill the sampling theorem. As long as the sampling theorem is satisfied, the numerically reconstructed image has no loss of information. The angle between the object and reference waves is dependent on the

distance of the object from CCD and its size. Therefore the simplest way to reduce the angle between waves is either by reducing the apparent size of the object or by increasing its distance from CCD. The off-axis digital holographic experimental arrangement for objects roughly equivalent to CCD sensor size is shown in Figure 2.13 [62]. The angle between object and reference wave can be controlled by tilting the mirror.

Figure 2.13. Experimental set-up of digital holography [62]

To study smaller objects, a microscopic objective is being used to magnify the object wave and then interfere it with the reference wave [63-64]. The optical set-ups of digital holographic microscope (DHM) for reflection and transmission geometries are shown in Figures 2.14 and 2.15 respectively.

High magnification ratio can also be achieved by a geometrically magnified diffraction pattern called lensless digital holographic microscope [65], the experimental arrangement is shown in Figure 2.16.

Figure 2.14. Digital holographic microscope set-up with reflection configuration [63]

Figure 2.15. Digital holographic microscope set-up with transmission configuration [72]

Figure 2.16. Lensless digital holographic microscopic set-up [65]

For large objects, different schemes have been proposed to modify the optical recording geometry. A diverging lens is used to demagnify the object as shown in Figure 2.17 reduces the object spatial frequency [66]. The wavefield of the virtual image rather than the object is recorded by the CCD. By placing the divergence lens between object and the CCD, the object angle projected on to the CCD is reduced.

Figure 2.17. Imaging geometry to reduce the spatial frequency

Recording of holograms of large objects by lensless geometry is shown in Figure 2.18 [67]. An aperture is placed between object and the CCD to selectively control the spatial frequencies produces on the CCD sensor. The aperture stops the rays from making large angles with the reference beam and results in a low spatial frequency interference pattern within the spatial resolution of the recording CCD.

Figure 2.18. Lensless digital holography arrangement for large objects

2.2.2.1 Imaging applications

- Digital focusing and phase reconstruction

The unique advantage of digital holography is the capability of recording full field information of 3D objects in digital form and the ability of numerical focusing at any arbitrary plane. In addition, the numerical reconstruction of complex amplitude allows the visualization of amplitude contrast as well as pure phase images. The phase contrast image provides information of the optical phase distribution inside the object.

E. Cucho et al. [62] developed the off-axis digital holography with application to phase contrast imaging. For phase contrast imaging, numerically defined reconstruction wave must be a digital replica of the reference wave that was used for hologram creation. Quantitative phase contrast images were demonstrated and it can be used directly for the applications in optical metrology. The quantitative phase contrast image used for surface profilometry with step height resolution of 10nm is presented. The presence of a microscopic objective (MO) in DHM produces a curvature in the object wavefront, which affects the reconstructed phase image. However there are no effects of curvature on amplitude contrast image. Methods to remove these phase aberrations in Fresnel off-axis digital holography have been developed [63-64, 68]. Applications of phase contrast imaging by DHM have been applied in different fields such as, surface profilometry [62, 69], and pattern recognition [70]. Biological samples analysis by transmission DHM has been presented [71, 72]. Applications of lensless DHM for biological sample study and 3D shape measurement have also been presented [65, 73].

Other significant application of digital focusing is for particles imaging in 3D which generally performed using in-line DH and will be covered in article 2.3.

- Speckle noise reduction

The presence of speckle noise due to coherent light in DHM sometimes does not fulfil the requirement of high-resolution imaging. This effect is minimised by reducing the coherence of the light source. DHM with short coherence light source has been described in literature [65, 74-75] including the use of LED illumination [76]. To achieve higher resolution (called super resolution) in digital holography, a grating can be placed in front of the specimen as discussed by Liu. et al. [77]. Other works on DHM such as, spatial filtering [78], phase shifting in digital holography and application to microscopy [79-80], microgravity materials applications [81], and testing of high aperture micro-optics [82] have been presented.

2.2.2.2 Measurement applications

The most remarkable application of holography is the interferometric comparison of diffuse wavefronts. It makes vast generalization of interferometry to the measurement of displacement and surface deformation of opaque objects. It involves the double exposure method from two different states of the object. By reconstructing the hologram, the two wavefronts interfere with each other and produce a fringe pattern that describes the changes that occurred between the two states of the object.

Numerical reconstruction process in digital holography makes it possible to numerically measure the intensity and phase for both states of the object directly from the holograms, which is not possible in conventional holographic interferometry. It is possible to calculate the interference phase directly from the holograms, which is the phase difference between the two object waves [83-84]. Also the other methods of optical metrology e.g. shearography and speckle photography can be numerically obtained from digitally recorded holograms [85]. Methods for micro- deformation measurement based on the principle of off-axis digital holographic interferometry have been studied [86-87]. The interference fringe pattern is difficult to obtain if displacement is less than half of the optical wavelength. Generally phase shift method is used in such situations, but it needs more than 3 images for phase shifting and phase reconstruction. A hybrid method based on gray scale of CCD and holographic interferometry has been presented for nano-scale deformation measurement [88].

The increased complexity of microsystems i.e. Microelectromechanical systems (MEMS) demands sensitive and robust interferometric techniques. Integration of principle the digital holography interferometry with microscopy, called hybrid holographic micro interferometry provides a novel solution for measurements of microsystems [64, 89-93]. Strain analysis has been described by digital holographic methods [94-95]. By illuminating the object from three directions, all the three surface displacement components (x, y, z) are calculated during reconstruction process [96]. These components can be used to find the displacement gradient or strains on the surface.

The recording of holograms with short exposure time is required to study the dynamic deformation. The instantaneous study of the dynamic behaviour of the object is done using pulsed digital holography. Digital holograms, at two different time are recorded using a pulse laser and reconstructed phase subtraction gives the deformation same as for double exposure holography. Transient vibration analysis using pulse digital holography has been studied [67, 97]]. Four pulses (with few micro-second duration) of a Ruby laser have been used to measure the transient vibration state of the object. Sensitivity has been increased by illuminating the object from different directions [98-100]. It allows the parallel evaluation of three-dimensional dynamic measurements i.e. for both in and out-of plane measurements.

Recording of digital holograms with time average principle is used to study the vibration analysis [101]. The capability of numerical measurement methods to extract informations, which were not possible with conventional holographic interferometry, have been presented [102]. The concept of zero crossing phase of time average Bessel fringes allows a highly contrasted determination of the time average dark fringes [103].

2.3 In-line digital holographic system

2.3.1 System development based of in-line geometry

Digital recording of holograms using CCD sensor need to fulfill the sampling theorem across the sensing area. The poor resolution of CCD sensors restrict the interference angle between object and reference waves. In comparison to well developed off-axis set-up, the in-line system helps to relax the spatial resolution requirement on the CCD sensor

and increase the flexibility of the system. In-line geometry significantly improves the performance of digital holography system and shows the higher resolution and accuracy [104]. It is also shown that the in-line digital holographic system shows better performance due to its higher spatial-bandwidth product which provides a larger field of view and higher imaging resolution than the off-axis set-up [105].

The problem associated with using in-line holography is the overlapping of zero-order term and twin image waves with real image wave. Having data in digital form provides the numerical solution to suppress these unwanted waves. Various methods to suppress the zero order have been proposed, they are; numerically subtracting the average intensity of all pixels from the recorded digital hologram [106], by reconstructing high pass filtered hologram matrix with low cut-off frequency [106], using the Laplacian of the detected hologram for reconstruction [107], phase shifting techniques [108], and numerical processing the holograms with different recording parameters [109].

Based on the in-line geometry both reflection and transmission system has been developed:

- Reflection microscopic set-up

Traditional digital holographic microscope is off-axis type and is commonly used to study phase objects. In case of objects with diffusely reflecting surfaces, since the microscopic objective has short working distance at higher magnification, illuminating the object is a problem. To ensure sufficient working distance for good illumination of

objects, integration of long distance microscope (LDM) with a digital holographic system has been proposed [90, 110]. The experimental set-up is shown in Figure 2.19.

Figure 2.19. Hybrid holographic microscope set-up [90]

- Transmission set-up

An in-line digital holography set-up for particle distribution measurement in transparent media is shown in Figure 2.20. A collimated laser beam illuminates the particles field [111]. The wave diffracted by the particles forms the object wave and the unaffected wave acts as the reference wave. The hologram thus formed is recorded using a CCD.

Figure 2.20. In-line digital holography set-up for particles measurement

An optical set-up for a lensless in-line digital holographic microscope [112-113] is shown in Figure 2.21. The laser beam passing through a pinhole illuminates the object and forms a geometrically magnified diffraction pattern on the CCD. The interference between the

waves scattered by the object and un-scattered waves forms the hologram which is recorded by the CCD.

Figure 2.21. Lensless digital holographic microscope

2.3.2 Current research status

- Imaging

The imaging capability of in-line digital holography and its comparison with off-axis system is presented [104]. To implement in-line digital holography in microscopy, high magnification ratio is achieved, either by geometrically magnified diffraction pattern (also called lensless digital holographic microscope) [113] or by using an imaging system i.e. microscopic objective [114]. The numerically reconstructed image from the lensless in-line digital holographic microscope of a US air force (USAF) target, with a resolution of $2.2\mu m$ is presented [51].

Particles Imaging

Particles analysis is one of the major imaging application of in-line digital holography. Direct recording of holograms by a CCD and numerical reconstruction method can also be applied for particles analysis [115]. The numerical aperture (NA) of digital particle

hologram is limited to less than 0.1 [116]. The small NA results in a remarkably large depth of focus in the reconstructed particles image. The slow intensity variation in the particles image along z-direction during reconstruction increases the error in the exact position measurement of particles. Kreis et al. [117] proposed to increase the depth resolution for particles measurement by combining the tomographic methods with digital holography.

Potential applications of digital holography for particle position and size measurement (for particles greater than $80\mu m$ in size) have been discussed [118]. The accurate axial position of the particles can be measured by the reconstructed intensity profile along the depth. Also the size of the particles can be simultaneously determined. In order to improve the depth localization of particles, the reconstructed amplitude profile has to be maximized at the exact reconstruction distance. Furthermore, the complex amplitudes of reconstruction field have been presented to determine the accurate axial position of the particles [116]. It was found that, reconstructed particles wavefield amplitude experiences some oscillations when reconstructed by convolution method with the Fresnel function [119], the solution is proposed by using a window in the expression of the reconstruction function [119]. A diverging beam has been presented for the analysis of both opaque and transparent particles with sub-micrometer level resolution [120].

The limited size and number of pixels do not resolve parts of the interference fringes and may result in under-sampled data (digital hologram) recorded by the CCDs. Signal recovery from an under-sampled digital hologram recorded with large number of

particles has been studied [121]. Numerical reconstruction of 3D particles field based on wavelet transformation methods presented an improvement in the accuracy of particles measurements [122-123]. Studies on digital holographic particle image velocimetry (DHPIV) have also been presented [124-125].

- Measurements

Deformation measurement is performed by recording two holograms; one corresponding to a reference state and other for the deformed state of the object. A broad range of amplitude displacements can be measured with high resolution. The study of a MEMS device by in-line digital holographic interferometry has been presented [126]. The interference phase pattern shows the out-of plane deformation in pressure sensor. Demodulation of these 2π wrapped interference phase gives the exact values of profiles of phase variation over the test surface.

Hybrid in-line holographic microscope is presented for interferometric measurements of microstructures [90]. The system is called in-line digital micro-holo-interferometry (IDMHI). The performance of IDMHI system has been tested in interferometric experiments for study of static deformation in microstructures [110].

2.4 Analysis and system proposal

Gabor proposed the concept of holography for wavefront reconstruction; the system was based on in-line geometry. The fundamental problems with in-line holography is the overlapping of the zero-order undiffracted wave and twin image wave with the real image

wave, that results as a disturbance in the focused real image wave. Perhaps, alongwith these limitations, in-line digital holography has been applied in some applications, mainly in the field of particles field 3D analysis. The advent of the laser enabled Leith et al [42] to develop the concept with off-axis holography. By introducing an off-set angle between object and reference waves to separate the zero-order and twin image wave term from real image wave. Thus the real image quality is significantly improved and free from interruption and hence has played a crucial role in visualization and metrological applications of holography.

By handling the hologram information in digital form offers the possibility of numerical solutions to the limitations associated with conventional holography. We have seen that off-axis digital holography has its own advantages over conventional holography despite the reduced resolution of the imaging device. On the other hand, in-line digital holography has the ability to bring holography into a full circle. The ability to pre-process as well as quantify the information is of enormous need in fields imaging and measurements, and thus need to be explored.

2.4.1 Lensless in-line system for dynamic 3D imaging and measurements

Holography provides the method for lensless imaging techniques and has been demonstrated successfully in a wide range of applications as discussed before. The principle works when the object illuminated with a coherent light interferes with a reference beam. It not only maps the intensities of the object, as in normal diffraction

patterns, but also encodes information about the phase of the light that is otherwise intrinsically lost.

The capabilities of in-line geometry in digital holography have several advantages over off-axis geometry. The most common and existing in-line based system uses the phase shifting techniques [127], requiring the recording of at least three digital holograms corresponding to the same state of the object. Thus it is not suitable for dynamic applications. The other in-line based system is called the image plane holography [128], where the object image is focused on the CCD sensor surface using a lens. Along with using the lens, the main limitation with image plane in-line digital holography is the heavy computational reconstruction process.

In order to develop a novel digital dynamic holographic system, it is proposed to explore a system based on lensless in-line digital holography for dynamic imaging and measurements applications.

- Microscopy using the lensless system

In order to study smaller size objects using digital holography, there is a need to magnify the object wave. In holography basically two methods are used to get magnification, called pre-magnification and post-magnification. In pre-magnification methods, a lens is used to magnify the object wave same as in conventional digital holography microscopic system where microscopic objective is generally used for magnification process [114].

While in post-magnification, the reconstruction process is used to get the magnification from the holograms recorded without magnification [44].

Another interesting approach is to get magnification without using any lens [120]. In such lensless microscopic approach the object is illuminated by a highly diverging beam, and thus geometric magnification is achieved by the divergence of the light itself. The integration of lensless microscopic concept with in-line digital holographic method provides the new significant tool for optical metrology. In this project, the capabilities of in-line based digital holography and its integration with lensless microscopy system are explored and experimentally analyzed for dynamic imaging and measurement applications.

2.4.2 Research proposals

In addition to the demand of high 3D resolution and microstructures measurements, the identification of microscopic scheme is the significant task for successful development of digital holography in dynamic imaging and micromasurement. For micro size objects distributed in 3D, microscope objectives based imaging system is not sufficient because of short working distance and limited depth of field. This kind of imaging system is also not applicable for the structures with diffusely reflective surfaces. The suitable microscopic scheme, therefore, has to cover the needs of 3D micro imaging and microstructures with high resolution and magnification.

In this project digital holography is extended for dynamic 3D imaging and micro-metrology. The size of the test samples and image acquisition and processing for dynamic analysis are major challenges that have to be overcome. Conventional off-axis digital holography is unable to meet these requirements due to inefficient use of the CCD and reduced resolution. In contrast, in-line digital holography system uses the full sensing area of CCD along with high imaging resolution and larger field of view. The unique properties of in-line digital holography, such as capability of whole field information storage in a single hologram with higher accuracy, together with the efficient use of computer technology for fast data processing, enables it to be developed as a dynamic micro-metrological tool for dynamic imaging and measurements of Microsystems and MEMS devices.

The development of lensless in-line digital holographic microscopy system is proposed. The aim is to develop the systems based on transmission and reflection configuration for dynamic imaging and measurement applications. The methodology is developed based upon the studies on mechanism of lensless in-line digital holographic microscopic geometry and optimization of reconstruction algorithm in imaging and measurements. The study of various parameters which effect the system performance are one of the important tasks of the project, followed by the experimental investigations on dynamic imaging of micro-particles and for the measurement of deformation and vibration of MEMS devices.

2.5 Chapter summary

In this chapter an overview of optical based techniques was first presented for imaging and measurements applications. The advantages of holographic techniques over the other existing techniques were discussed, followed by the detailed discussion on the development of the digital holography (DH) methods. The current research status of DH for imaging and measurement application was discussed. The development of in-line based digital holographic system and their advantages over the off-axis system are also discussed along with their applications particularly in particles imaging and interferometric measurements. In order to develop a novel digital dynamic holographic system for particles imaging and measurements, a lensless in-line based microscopic system is proposed.

The thesis work focuses on the development of the methodology of lensless in-line digital holographic methods for dynamic situations, both for transmission and reflection based microscopic systems. Micro-particles imaging in 3D and dynamic analysis are presented for the transmission system. For reflection system, the method for dynamic measurements is presented and a double exposure time average method is developed for vibration analysis. The experimental validation of the method is presented, and explored for dynamic MEMS characterization.

CHAPTER 3

ADVANCES IN IN-LINE DIGITAL HOLOGRAPHIC SYSTEMS

In-line digital holography has several advantages over the off-axis geometry e.g. larger field of view and higher imaging resolution. In this chapter, advances with in-line digital holographic systems are presented. The study of the digital recording mechanism of in-line holograms and optimization of reconstruction methodology are studied. Advancement of the lensless in-line digital holography microscopic system is presented, both for transmission and reflection conditions. Parameters of the system, that affect the resolution of the system, are studied and magnification retrieval mechanism for converging reconstruction wave is shown. The lensless in-line microscopy set-up is proposed to implement in dynamic applications, both for imaging and measurements.

3.1 In-line digital holographic system study

For in-line digital holographic configuration, the object and reference wave propagates along the same optical axis. In comparison to off-axis geometry, in-line system requires smaller recording distance between the object and CCD sensor. This improves the system performance and it utilizes the full area of CCD for image reconstruction.

3.1.1 Digital recording requirements

- Collimated reference wave

The limited resolution of CCD sensors limits the angle θ (called interference angle) between the object and reference beams to few degrees only. For exact recovery of the object information during reconstruction process, the sampling theorem requires that the interference fringe spacing must be larger than the size of two pixels of CCD i.e.

$$\theta < \frac{\lambda}{2\Delta\xi} \quad (3.1)$$

where λ is the wavelength of light used and $\Delta\xi$ is the pixel size of the CCD. The recording distance, between the object and CCD, is an important parameter to control the interference angle.

For efficient utilization of the recording sensor, it is important that the sampling theorem must be fulfilled across its entire CCD sensing area. Thus, for a certain lateral size of the object, the recording distance (between object and CCD sensor) should be greater than a particular minimum value. The optical geometry of in-line digital holography with collimated reference wave is shown in Figure 3.1.

Figure 3.1. In-line recording mechanism using collimated reference wave

Let the maximum possible interference angle be $\theta_{\max}$, corresponding to object size S_o , such that the sampling theorem is not violated. For such a condition, the minimum recording distance is given as [104],

$$(d_{\min})_{in-line} = \frac{\Delta \xi}{\lambda} (N \Delta \xi + S_o) \quad (3.2)$$

Where N is the total number of pixels along ξ direction.

- Diverging Reference wave

The minimum distance requirement for in-line digital holography using collimated reference wave is given by Equation (3.2). This minimum distance requirement can be further reduced by using a diverging reference wave. This is because, the fringe spacing (Δ) of interference pattern depends on the angle between the waves ($\Delta = \lambda / \sin \theta$). The fringe spacing increases when the angle between two waves decreases. The recording mechanism of in-line digital holography using diverging reference wave is shown in Figure 3.2.

Figure 3.2. In-line recording mechanism using diverging reference wave

The smaller recording distance improves the system capability [105]. Increasing the divergence of the reference wave provides the flexibility to record holograms at smaller recording distances. It is explained in Figure 3.3, where the recording mechanism of digital holograms at three recording distances is shown. In order to fulfill the sampling condition requirements, there is a need to maintain the same interference angle corresponding to all three conditions. This is achieved by changing the divergence of the reference waves.

Figure 3.3. Recording of in-line hologram using diverging reference wave

3.1.2 Numerical reconstruction

The coordinate system of digital holographic system is shown in Figure 2.11. The diffracted wave from the object (with object plane (x, y)) to the hologram plane (ξ, η) , is called the object wave $O(\xi, \eta)$. The interference of object wave and reference wave $R(\xi, \eta)$ produces an intensity field at the hologram plane. The interference pattern can be written as,

$$H(\xi, \eta) = |O(\xi, \eta)|^2 + |R(\xi, \eta)|^2 + O^*(\xi, \eta)R(\xi, \eta) + O(\xi, \eta)R^*(\xi, \eta) \quad (3.3)$$

The first term $|O(\xi, \eta)|^2$ is the object wave intensity, which can be obtained by the multiplication of illuminating wave and object intensity. The physical behavior of the object wave is generally non-uniform and depending upon the system parameters such as object size, shape, and recording distance. The second term $|R(\xi, \eta)|^2$ is the intensity of the reference wave and it depends on its corresponding geometry. The sum of the first two terms of the Equation (3.3) is called the DC or background intensity, and causes the zero-order diffraction term during reconstruction process. The third and forth terms in the Equation (3.3) represent the interference patterns, which contribute to the formation of image of the object during reconstruction. These two interference components are conjugate to each other, and the reconstructed wavefield represents the two images which are conjugate to each other. Thus, these two reconstructed images are called the real and conjugate images.

Figure 3.4. Reconstruction geometry of in-line digital holography

The reconstruction geometry of in-line digital holography is shown in Figure 3.4. The reconstruction wave is incident on the hologram plane. All the three waves (zero-order term, real image wave, conjugate image wave) are generated by the diffraction process. When the reconstruction wave is conjugate of the reference wave, the real image is focused at the same distance as during the hologram recording process. The conjugate image is focused at the same distance but in opposite direction, and thus appears as the out-of-focus image. Because of the in-line geometry the zero order and conjugate image waves overlap with the real image wave. The zero-order term is non-diffracted and appears as a uniform background with the focused real image wave. The presence of out-of-focus conjugate image wave at real image plane creates the background noise.

- Suppression of unwanted in-line waves

In in-line digital holography, the zero order term appears as a bright background overlapping the reconstructed real image. It has to be eliminated from the reconstructed image. Digital methods were proposed for suppression of the zero-order term. The simplest method to remove the zero-order term is by measuring the intensities of object wave $I_o(|O(\xi, \eta)|^2)$ and reference wave $I_R(|R(\xi, \eta)|^2)$ separately, and then subtract them from the recorded hologram before reconstruction. Thus the resulting hologram becomes,

$$H^*(\xi, \eta) = H(\xi, \eta) - I_o - I_R \quad (3.4)$$

This process of suppression of zero order term is not preferred because of the requirement of higher experimental efforts due to additional measurements.

The zero order term can also be suppressed by numerically subtracting the average intensity of all pixels $H_m(k\Delta\xi, l\Delta\eta)$ from the recorded digital hologram $H(m\Delta\xi, n\Delta\eta)$ [106],

$$H'(m\Delta\xi, n\Delta\eta) = H(m\Delta\xi, n\Delta\eta) - H_m(m\Delta\xi, n\Delta\eta) \quad (3.6)$$

Where

$$H_m = \frac{1}{MN} \sum_{k=0}^{M-1} \sum_{i=0}^{N-1} H(m\Delta\xi, n\Delta\eta)$$

Then the reconstruction of H' is free from zero order wave. Other techniques developed for background suppressions are discussed in section 2.3.1.

Phase shifting method is used to suppress the effect of zero-order term and conjugate image simultaneously [108]. But the recording of phase shifted holograms restricts the application areas, and cannot be used in dynamic applications. In this project the system geometry is modified and novel reconstruction methodology is developed for effective use of in-line geometry especially for dynamic applications.

3.1.3 Optimization of the set-up

- Analysis of digitally sampled holograms

The spatial frequency ($\nu = 1/\Delta$) of the micro-interference pattern of object and reference waves at the hologram plane depends on the angle between them. For collimated reference wave, the angle between object and reference waves changes with the recording distance d . Figure 3.5 shows the effect of changing the angle on the spatial frequencies at the hologram plane, from the centre of the CCD sensor to its end. The quantities involved for this plot are for a laser wavelength of $\lambda = 0.532\mu m$ and an object size of

5mm. Three different distances 100mm, 150mm and 200mm are shown as an example, the general trend of the behavior can be clearly seen. The spatial frequency is smaller at the central region of the sensor, and increases as we move outwards. Also higher spatial frequencies are available at smaller recording distances. It shows the information storage capability during digital sampling at smaller recording distances.

On the other hand, for a diffuse object, the average objective speckle size (Ω) (or spatial frequency f_s) at a distance d from the object is [24],

$$\Omega = \frac{1}{f_s} = \frac{\lambda d}{S_o} \quad (3.7)$$

Figure 3.5. Spatial frequency variation of micro-interference pattern at the CCD plane

The object information is encoded in the objective speckles. The sensitivity of numerically reconstructed object wave is proportional to the spatial frequency of speckles sampled during the hologram recording. The sampling of the interference of object and

reference waves, and of individual speckles are the two different phenomena, which separately affect the numerically reconstructed information.

Increase in objective speckle size results in the decrease in the spatial frequencies of the speckled object wavefront. The reduction in the spatial frequency will reduce the sensitivity of the information represented by the speckles. The information of the object wave is modulated in the speckle pattern. The smaller the object to CCD distance provides the smaller speckle size and thus the large information capability. Figure 3.6 plots the variation of objective speckle size, spatial frequencies of the speckles, and spatial frequencies of micro-interference (hologram) between the object and reference wave as a function of object to CCD distance. The parameters considered for this plot are same as that for the plot shown in Figure 3.5.

Figure 3.6. Spatial frequency of Speckles and holographic fringes as a function of recording distance

To experimentally demonstrate the effect of recording distance on measurements, consider the recording of a hologram with the object to CCD distance of 295mm, 420mm, and 540mm, using in-line geometry. The object, a 5 mm diameter circular aluminium diaphragm is illuminated by a $0.532\ \mu\text{m}$ laser and holograms are recorded using a CCD having 1500×1500 array of $9\ \mu\text{m}$ square pixels. The effective area of the CCD capable of sampling the interference between the object and reference waves are shown for distances smaller than (Figure 3.7 (a)), equal to (Figure 3.7(b)) and greater than (Figure 3.7(c)) $d_{\min}$ (as discussed in Equation (3.2)). The maximum spatial frequencies of the interference fringes corresponding to these three distances are 117.8 lines/mm, 82.8 lines/mm, and 64.4 lines/mm. Since the CCD can have a maximum spatial frequency of 111.1 lines/mm thus for the first case, the number of pixels that can resolve the interference pattern is less then the total number of pixels of the CCD, while for second and third cases all the pixels can sample the interference pattern. Thus some of the spatial frequencies present on the object are lost in Figure 3.7(a) while all information is recorded in the other two figures.

Figure 3.7. Digital sampling of holograms for recording distances (a) smaller, (b) equal, and (c) larger than $d_{\min}$

Consider on the other hand, the objective speckle size at these three distances. Based on Equation (3.7), the smallest speckle size (or maximum spatial frequency of speckles) at these three distances are $31.34 \mu m$, $44.69 \mu m$, and $57.46 \mu m$ (or the spatial frequencies are 31.9 lines/mm, 22.3 lines/mm, and 17.4 lines/mm). This suggests that the sensitivity is higher at smaller distances.

Figure 3.8. Interference phase pattern for at different recording distances (a) 295mm, (b) 420mm, and (c) 540mm

To demonstrate this effect, the out-of-plane deformation of the diaphragm is measured. Two holograms with a deformation of about $5.6 \mu m$ were recorded corresponding to each of the recording distances. The interference fringes and their corresponding line profile, obtained by phase subtraction of two different states of object are shown in Figure 3.8(a)-(c). At larger distances the fringe contrast has reduced since the speckle size is approaching the fringe spacing. A plot of the intensity trace along the centre line as shown in the figure

highlights the situation. For shorter distance the fringe pattern follows the familiar modulo 2π distribution but as the distance increases parts of the fringe contrast reduces greatly.

- Frequency analysis of the system

Spatial bandwidth product

The recording of digital holograms is performed by using the coherent optical systems. During reconstruction process the coherent optical system is numerically simulated and thus provides the complex object wavefront that was reflected or refracted by the object during recording process. Frequency analysis is the most prominent method to characterize the coherent optical systems. For digital holography, the study of spatial bandwidth product of coherent optical system provides better understanding for optimizing the optical system.

In digital holography, the holograms are digitally sampled by using Whittaker-Shannon sampling theorem [48]. During numerical reconstruction process, the reconstruction function is band limited and suitably spaced array of the sampled values [52]. This is because the distribution function of hologram contained substantial spectrum values in its finite region, and so considered as band-limited. At the recording plane, let $f_\xi \times f_\eta$ represents the area in spectral domain, and $S_\xi \times S_\eta$ is the spatial dimension of the space-limited function. Then the quantity $S_f = S_\xi S_\eta f_\xi f_\eta$ is called the spatial bandwidth product. For no loss of information during the recording process, it is required that the S_f of the system should be larger than the object. Thus the spatial bandwidth product of the system during hologram recording evaluates the system imaging performance.

Consider Figure 3.1, let for one dimensional case, object with lateral dimension S_o is band limited within f_o , this gives spatial bandwidth product at the object plane as $S_f^o = S_o f_o$. For the holographic process the object wave is diffracted in Fresnel region, the propagation of beam, incident normally to the object and then modulated by the object spatial frequency γ_o . The angle of diffraction is $\delta = \lambda \gamma_o$ [48], where λ is the wavelength. Thus at the hologram plane, the lateral displacement of the diffraction beam is $\lambda \gamma_o d$. It means if a beam interacting at the object plane at point x_p' with spatial frequency γ_0 (i.e. coordinate (x_p', γ_0)) will incident at the hologram plane $x_p' + \lambda \gamma_o d$ with frequency γ_0 (coordinate $(x_p' + \lambda \gamma_o d, \gamma_0)$).

At hologram plane, the in-line interference pattern of object wave and reference waves can be written as $H(x_\xi) = |O|^2 + |R|^2 + 2OR \cos(2\pi \gamma_0 x_\xi)$. It implies that the frequencies range of interference is equal to that of object. The spatial bandwidth product of the hologram is therefore given as

$$S_f^H = (S_o + \lambda d f_o) f_o = S_f^o \left(1 + \frac{\lambda d f_o}{S_o}\right) \quad (3.8)$$

For reliable recording of object, this spatial bandwidth product should be at least equal to that of the hologram.

In case of digital recording, the effect of digitization by introducing the CCD sensor with $M \times N$ number of pixels with size $\Delta \xi \times \Delta \eta$ has studied. In such case the 2D spatial bandwidth product can be given as [105]

$$S_f^H = [M - \frac{(M \cdot \Delta\xi)^2}{\lambda d}] [N - \frac{(N \cdot \Delta\eta)^2}{\lambda d}] \quad (3.9)$$

Thus the number of sensitive pixels shows the imaging performance of the system. More number of sampling points improves the resolution and imaging quality.

Thus the requirement of smaller recording distance allows recording the higher spatial frequencies of the object. In comparison to off-axis geometry, in-line geometry provides less constraint to the effective field of view, which provides the recording of more details of the object. This results in higher imaging resolution and sensitivity of amplitude and phase information during reconstruction process.

- Requirements for convolution method of reconstruction:

Convolution method for reconstruction is most effective for smaller reconstruction distances, and thus it is suitable for the case of in-line digital holography. In convolution approach, the product of the transfer function with the Fourier transform of the product of hologram and reconstruction wave is calculated (Equation (2.18)). The transfer function is defined as the Fourier transform of the impulse response. From the frequency analysis of digital holography, it was found that the finite impulse response restricts the transfer function to a finite rectangular window [57]. The amplitude spectrum is nearly flat for reconstructed frequencies over the width of the window and zero outside. The maximum width of the transfer function (equal to the size of the CCD array) is found at the reconstruction distance $N\Delta\xi^2/\lambda$ for a CCD with N pixels of size $\Delta\xi$, where λ is the wavelength of light used. This width of transfer function decreases with increase in reconstruction distance. To obtain the best resolution during reconstruction, the transfer

function should be expanded to reconstruct all the significant frequencies contained in the original digital hologram. This can be achieved by selecting the recording distance as,

$$d < \frac{N(\Delta\xi)^2}{\lambda} \quad (3.10)$$

Figure 3.9. Behavior of transfer function for convolution method of reconstruction

Thus the recording distance should be as small as possible without violating the sampling theorem. To demonstrate this, the transfer function for a CCD with 500×500 pixels of size $9\mu\text{m}$ is calculated for a wavelength of $0.6328\mu\text{m}$. For these parameters, the transfer function has maximum width at the distance of 64mm . The transfer functions and their

corresponding intensities at the distances of $65mm$, $85mm$ and $105mm$ are calculated and are shown in Figure 3.9. It is clear that for larger reconstruction distance the transfer function area becomes smaller. The reconstructed phase values are valid only where the transfer function has non-zero values, the phase data outside this region contribute to numerical noise.

3.1.4 Advantages with in-line geometry

Some of the important properties of in-line digital holography are summarized as follows:

- ❑ The spatial resolution requirement of CCD sensors is relaxed for in-line digital holography in comparison to off-axis holography. Also the full sensor area is efficiently utilized in image reconstruction.
- ❑ Higher spatial bandwidth product can be achieved during digital sampling of in-holograms, and thus provides the higher information recording capability which results as the higher imaging resolution and sensitivity.
- ❑ Lateral resolution of the image reconstructed by FT method increases with decrease in the recording distance. Thus higher resolution can be achieved with in-line geometry. On the other hand, the convolution approach also effectively suitable for shorter recording distances.
- ❑ Speckle noise is generated in the image plane because of the coherence and random phase distribution of each point of the object. Small recording distance requirement in in-line digital holography also reduce the noise caused by speckles.

- ❑ In comparison to off axis geometry, in-line set-up is easy to align with less effort to equalize the optical path difference between object and reference wave to keep it within the coherence length of the laser.

3.2 Lensless in-line microscopy systems study

Digital holography, with collimating object wave provides no magnification. It has two limitations; first is the poor lateral resolution because of the pixel size of available CCD sensors and the second is poor depth resolution for 3D imaging. In order to get magnification without using any lens system and to overcome these problems, a diverging wave can be used in place of the collimated wave to illuminate the object. The divergence of the wave provides the geometrical magnification and thus improves the system resolution. At the same time numerical aperture of the system is increased which results in the better depth resolution. The study of a lensless microscopic system is presented here.

3.2.1 Transmission system

3.2.1.1 System configuration

Lensless in-line transmission digital holographic microscopy (LDHM) system is shown schematically in Figure 3.10. A laser beam is focused on a pinhole using a microscopic objective (MO). A highly diverging spherical wave emerges from the pinhole. The divergence depends on the size of the pinhole, and it provides the lensless magnification of the system. The object is placed inside the cone-shaped spherical diverging wave, and the scattered light from the object is geometrically magnified and interferes with the

unscattered spherical reference wave. Thus the system is suitable only for smaller objects occupying the segment of light coming from the point source. The interference pattern is recorded by the CCD sensor as shown. Let D be the distance between point source and CCD and l be the distance between point source and object plane, then the geometric magnification of the system become D/l .

Figure 3.10. Lensless in-line digital holographic microscopy configuration

Consider $R'(r)$ to be the optical wave coming out from the pinhole. This can be divided into two parts; the first part is the unscattered spherical reference wave denoted by $R(r)$, and the second part is the scattered wave from the object denoted by $O(r)$. Thus the hologram can be written as,

$$H(r) = |O(r) + R(r)|^2$$

$$= |O(r)|^2 + |R(r)|^2 + O^*(r)R(r) + O(r)R^*(r) \quad (3.11)$$

The first two terms in the above equation create the additional background light in the real interference term represented by the last two terms. This additional background light creates the zero-order undiffracted term during the hologram reconstruction. A possible

way to subtract this background term is by creating the contrast hologram [120]. The other method is to apply a high pass filter to the hologram before reconstruction process as discussed before.

Figure 3.11. Reconstruction with converging reference wave

The reconstruction of object wavefield is performed using the converging wave as shown in Figure 3.11. The numerical reference wave is created digitally, by considering the parameters of recording system. It is focused at a distance same as the distance between pinhole and CCD sensor used during hologram recording process. For distance D between pinhole and CCD, the converging reference wave can be defined as, $R = A \exp[-ik(x^2 + y^2)/2D]$, here A is the amplitude and k is the wave vector.

The reference wave impinges normally onto the CCD. For the numerical implementation of the transform, Fresnel transform algorithm is used. The Fresnel transform can be

calculated by fast Fourier transform (FFT) algorithm which represents the Fourier transform of the point-wise product of digital hologram, reference wave and a quadratic exponential component. The reconstructed wavefront is a complex function and its amplitude is used to represent the object image. The quadratic phase factor is eliminated at the real image plane. Since the impulse response (and transfer function) is restricted to a finite rectangular window in digital holography, for a convergent reconstruction wave the additional quadratic phase introduces according to the convergence effect of the wave at the reconstructed real image plane. The convergence effect also results as in reduce in the reconstructed image size, which further decreases with increase in the reconstruction distance.

The object wavefield is reconstructed and its amplitude gives the images of the object in different sections parallel to the hologram plane. Thus it provide the 3D reconstruction of the image from the two dimensional hologram. Another advantage of such geometry is that, the twin image does not create any problem in the reconstructed real image [120]. This is because the twin image is on the opposite side of the real image and appears as a defocused image at the real image plane. In case of small objects, the amplitude of the twin image wave is significantly small at the real image plane. Also, when the hologram is reconstructed with a converging beam, the divergence of the out-of-focus twin image at real image plane further increases, and thus the amplitude becomes almost negligible compared with the real image wave. The lateral size of hologram also effects the twin image noise during reconstruction, the smaller lateral size increase the background noise created by the twin image [129].

3.2.1.2 System analysis

- Lateral resolution

In order to make sure the proper reconstruction of object image from hologram, the main requirement is the recording of proper holographic fringes. However, the lateral resolution of system depends on the numerical aperture (NA) and wavelength, similar to a conventional microscope. The NA of the LDHM system is defined by the range of angle over which the CCD can accept light coming from the pin-hole. According to the Rayleigh resolution criteria, the minimum distance Δx , between of two points to be resolved, is defined as [130],

$$\Delta x \geq \lambda / 2 \cdot (\text{NA}) \quad (3.12)$$

Figure 3.12. Effect of pinhole to CCD distance on lateral resolution of the LDHM system

(a) for 90mm, and (b) 45mm

The effect of system parameters on lateral resolution is studied and shown in Figures 3.12 and 3.13. Figure 3.12 shows the effect of numerical aperture by changing distance between the pinhole and CCD for a laser wavelength of $0.405\mu m$. Figures 3.12(a) and (b) shows the amplitude image of central part of the US air force target (USAFT) using a

pinhole $5\mu m$ in diameter at distances between pinhole and CCD (contains 1280×960 pixels size $4.65\mu m$) of 90mm (NA=0.033) and 45mm (NA=0.065) respectively, with similar magnification. The line profile as shown is plotted to see the effect on resolution. It is clear that as the NA increases by decreasing distances between pinhole and CCD, the resolution of the system is increased.

Figure 3.13 shows the effect of size of pinhole on the lateral resolution. Three amplitude images are shown reconstructed from the holograms, recoded using pinhole size of $10\mu m$, $5\mu m$ and $1\mu m$ respectively. The distance between pinhole and CCD is 40mm. The smaller pinhole size results in an increase in the resolution of the system.

Figure 3.13. Effect of pinhole size on the lateral resolution of the LDHM system for (a) $10\mu m$, (b) $5\mu m$, and (c) $1\mu m$

- Depth Resolution

The limitation of poor depth resolution with collimating wave in-line digital holography is improved in the case of LDHM. The depth of focus, defined in optical systems [130],

$$\Delta z \geq \frac{\lambda}{2 \cdot (NA)^2} \quad (3.13)$$

The NA of the LDHM system is not as high as the one compared to optical microscopic objectives. The depth resolution is also depend on the size of the object [123]. The intensity plot of reconstructed image along depth used to calculate the exact depth location, it will be discussed in Chapter 4.

Both lateral and depth resolution can be improve significantly, if hologram recorded with sufficiently larger CCD sensing area is placed close to the pinhole (with larger NA). Also, the size of pinhole significantly affects the resolution of the system. Smaller pinhole (ideally of the order of wavelength) increases the cone of the emitted light coming through it. This increases the NA of the system and thus improves the system resolution.

- Magnification and its retrieval for converging wave reconstruction

Magnification of the system is defined by the geometrical formula (D/l), where D is pinhole to CCD, and l is the pinhole to object distances. The position of the object plane controls the magnification of the system. In order to get the higher magnification the object needs to be placed nearer to the pinhole.

In order to record holographic fringes for a certain magnification, there are two main requirements; first the object should cover only a fraction of the spherical reference wave, so that there is proper interference between scattered object and unscattered reference waves. The second is to record at least three diffraction orders of the diffracted wave by the object for proper reconstruction of the object [44].

Reconstruction of holograms using converging reference wave and the Fourier Transform (FT) method results in smaller size of the reconstructed image. Also the reconstructed image size is reduced with increase in the reconstruction distance. As the recording distance increases, the magnification increases, but decrease in reconstructed image size neglects the effects of magnification. The pixel size along with the reconstruction distance for FT can be controlled by fictitiously increasing the hologram size by zero-padding [131]. For LDHM system, the requirement that pixel size has to be controlled in such a way that magnification effect corresponding to different depth is achieved.

For the FT method, reconstruction pixel size along the x - and y - axes changes with the reconstruction depth. To keep the analysis concise, we present equations only for the x -dimension, but the same equations hold for the y -dimension too. Specifically the pixel size changes as,

$$\Delta x' = \frac{\lambda d}{M \times \Delta \xi} \quad (3.14)$$

where $\Delta \xi$ and $\Delta x'$ are the pixel size in the x - dimension at the recording and reconstruction planes, respectively, λ is the wavelength, M is the total number of pixels along the x - direction and d is the reconstruction distance.

In order to have equal pixel size at reconstruction distances d_1 and d_2 the hologram size has to be increased by zero padding to M'_x , which is

$$M'_x = \frac{d_2}{d_1} M \quad (3.15)$$

Following reconstruction only the central $M \times N$ portion of the propagated wavefront is retained. Zero padding fictitiously increases the hologram size for larger reconstruction distances successfully compensating in this way the pixel resizing effect of the FT reconstruction method.

Figure 3.14. Diverging wave digital holography geometry

In the case of lensless microscopic holography a diverging wave is used to achieve magnification. The pixel size remains the same during reconstruction by using the zero padding as defined by Equation (3.15), but the magnification cannot be achieved because of converging reference wave which further decreases the pixel size during reconstruction. An additional zero padding of the hologram by a factor of $(D - d_1)/(D - d_2)$ is thus necessary, so that overall zero padding of the hologram becomes

$$M'_x = \frac{D - d_1}{D - d_2} \frac{d_2}{d_1} M \quad (3.16)$$

where D is the distance between the pinhole that used to create the diverging wave and the CCD sensor as shown in Figure 3.14. The additional zero padding compensates the effects of the diverging wave magnification so that on the whole the pixel size remains constant corresponding to magnifications at different reconstruction depths.

To experimentally demonstrate the method, an in-line lensless microscopy recording setup was used to record a hologram of a US air force (USAF) target. A blue diode laser ($\lambda = 0.405\mu m$) was used for recording and the beam was passed through $1\mu m$ size pinhole positioned $38mm$ away from the CCD camera. The CCD contains 1280×960 pixels of size $4.65\mu m \times 4.65\mu m$ each. To achieve different magnifications, three holograms were recorded at distances of $20.33mm$, $21.33mm$, and $27.07mm$. Figure 3.15 (a), (b) and (c) shows the reconstructed images corresponding to these three reconstruction distances by using the converging reference wave and FT method. Here the central part (containing 200×200 pixels) of the reconstructed images shows the central region (group 7) of the USAF target.

Figure 3.15. Reconstructions at different depths, (a) $20.33mm$, (b) $21.63mm$, and (c) $27.07mm$

It can be seen that image shifts towards the center in the reconstructed images as the distance increases. The magnification is supposed to be highest corresponding to the reconstruction image shown in Figure 3.15(c), but since the pixel size reduces with increase in reconstruction distance thus magnification does not appeared for this case.

Figure 3.16. Diverging wave reconstructions at (a) 21.63mm, (b) 27.07mm with zero padding to compensate pixel size, and (c) 21.63mm, (d) 27.07mm for zero padding to retrieve magnification

The effect of zero-padding is presented in Figure 3.16. Figures 3.16 (a) and (b) show the reconstruction after zero padding according to Equation (3.15) at distances 21.33mm & 27.07mm respectively, here considering 20.33mm as the reference distance (d_1). It can be seen that the image sizes corresponding to all the three distances (Figures 3.15(a), 3.16(a and b)) are same, thus the shifting has been eliminated, but the magnification effect still cannot be noticed. In order to retrieve the magnification effect, the zero-

padding of the holograms is required according to the Equation (3.16). This effect is shown in Figures 3.16(c) and (d) for the distance 21.33mm and 27.07mm respectively, again here 20.33mm considered as the reference distance for zero padding of the recorded holograms. The magnification effect can be clearly seen in the images, which is higher corresponding to the larger distance.

3.2.2 Reflection microscopy system

3.2.2.1 Optical systems

The reflection lensless microscopic system geometry is shown in Figure 3.17. A diverging laser beam from the fiber end provides the magnification in a lensless geometry. The beam is divided into two parts by using a beam splitter; one beam illuminates the sample and other incident on the plane mirror. The sample is illuminated by the diverging beam, coming from the beam splitter. The scattered light from the sample (called object beam) is combined with the other diverging beam, reflected from the mirror (called reference beam) and the resulting interference pattern is recorded by the CCD. The distance between object and CCD controls the magnification of the system. Thus the system is fundamentally same as the transmission microscopic system, except that a separate diverging reference beam is used because of requirements of hologram recording.

This set-up (patent pending) presents a lensless reflection microscopic geometry by using a very simple and compact optical set-up best suited for micro-size objects. The novelty of the system is the compact optical geometry with minimum number of optical

components (only a beam splitter and mirror). The effect of zero-order term and twin image wave can be suppressed as discussed in transmission case. The algorithm for magnification retrieving for converging wave reconstruction can also be used for magnification analysis of the system.

Figure 3.17. Lensless digital holographic in-line reflection microscope

The system shown in Figure 3.17 is best suited for the study of highly specular objects. The distance from point source to object is constrained by the beam splitter, which restricts the magnification of the system. Also the system is not best suited for the study of the diffused surface objects. It is because the scattered beam from diffuse surface is significantly smaller than the reference beam intensity, and thus does not provide good contrast of the interference pattern. These limitations of the system can be compensated by splitting the laser beam into two fibers. The set-up geometry is shown in Figure 3.18.

The output from a laser is coupled into a bifurcated single mode fiber. One fiber arm is used to illuminate the rough surface object with diverging beam. The scattered beam from the object, called object beam interferes with the diverging reference beam (or collimated reference beam) from the second fiber. The intensity of reference beam is controlled to match the object beam, by means of a variable attenuator. Polarization of both the object and reference waves are maintained same to get the best contrast of the interference fringes. The interference of object and reference beams are recorded on the CCD.

Figure 3.18. Lensless digital holographic in-line reflection microscope for optically rough surfaces

3.2.3 Advantages of lensless in-line digital holographic microscopic system

Most of the existing digital holographic microscopic systems use the microscopic objective and off-axis geometry [45-46]. For off-axis digital holography, only part of the

CCD is used in the reconstruction process. In comparison to off-axis geometry, the advantages with in-line geometry are larger field of view with higher imaging resolution [105]. Thus the digital in-line holographic system based on lensless microscopic geometry is a novel tool for optical metrology, it also provides a very simple and compact optical set-up. The transmission set-up is best suited for 3D imaging of micro objects, such as micro-particles analysis. On the other hand the reflection based system is well suited for reflecting micro size device imaging and characterization.

☐ Lensless micro 3D imaging

In lensless microscopic imaging there are no aberrations as compared to microscopic system contained MO or lens systems. Additionally a single hologram provides the full 3D information about the objects. This kind of system is thus most suitable for dynamic 3D microscopic imaging.

☐ Higher imaging resolution along with larger phase sensitivity

In comparison to off-axis system, the in-line system provides a higher resolution [105], it also improves the system capability in terms of imaging resolution and sensitivity. Also it provides the interferometric measurements for micron size objects.

☐ Compact and simple optical geometry

The system has a very simple optical geometry with fewer numbers of optical components, no requirement of expensive coherent sources, easy to align and package.

3.2.4 Limitations of the in-line lensless microscopy set-up

Following are the some limitations of the system:

❑ Limited magnification

Magnification of the system is limited because of system geometry. To achieve higher magnification, the object has to be placed very near to pinhole which is not practical in the set-up.

❑ Phase sensitivity reduces with increase in magnification

By increasing the magnification, the phase sensitivity reduces, which will be explained in chapter 5.

3.3 Chapter summary

In-line digital holography has the better imaging performance, it provides the higher imaging resolution along with larger field of view. The optical system analysis of in-line digital holography is presented and optimization methodology is studied. Smaller recording distance provides the higher spatial bandwidth product and thus represents the more information recording capability. The limitations of using the collimated object wave can be overcome by using the diverging object wave. Lensless in-line digital holographic microscopy (LDHM) analysis is studied both for transmission and reflection geometries. Optical system analysis, imaging performance, and study of parameters are presented for LDHM system.

CHAPTER 4

STUDY OF MICRO-PARTICLES IN A STATIC AND DYNAMIC VOLUME

The study of motion of micro-objects in volume has significant importance in modern science. Measurements of instantaneous 3D distribution of micro particles dispersed in a flow are required for many applications. The size, position, velocity and 3D distribution of particles within fluid or gaseous media can be determined with holographic techniques. Direct recording of holograms by CCD sensor and numerical reconstruction method can also be applied for particles analysis. The potential for measurement of the size, location, speed, and three-dimensional spatial distribution of particles make holographic techniques more popular than the existing techniques. In-line based digital holographic techniques are explored for particles analysis. A method of slicing of particles amplitude images in different depths is presented. For 3D micro-particles analysis, a reconstruction algorithm is developed to slice in-focus particles and experimentally verified. By using this algorithm, the defocusing effects of out-of-focus particles are minimized from the focused image plane and the effects of direct and conjugate waves suppressed without pre or post processing of holograms. Furthermore the advancement using lensless in-line digital holographic microscopy is explored for the precise 3D micro-particles study and dynamic analysis. New developments have been presented with the existing digital holographic methods. The methodology of dynamic analysis of micro-particles is presented. The method of identifying the particles in

particular planes based on intensity threshold is presented. Furthermore, this method is used to locate the dynamic particles in 3D with higher accuracy. The results have been presented with the 9.6 micron particles in flowing water.

4.1 Digital in-line holography for particles measurements

The study of micro-particles analysis in 3D requires the size, shape, velocity, and local particles density. Particle image velocimetry (PIV) is the methodology for investigating particles in a two dimensional cross-section of 3D volume [132], additionally by using the double exposure method, the velocity component of dynamic particles can be studied [133]. Laser Doppler anemometry (LDA) [134] and phase Doppler anemometry (PDA) [135] are variations of PIV. Holography is a powerful tool for recording 3D volumes, and is a method complementary to anemometry. In-line transmission system as discussed in the previous chapter has the potential for the measurements of size, position, and velocity of particles distributed in 3D.

4.1.1 Particles holographic imaging in 3D

In digital holography for micro-particles analysis, the particle field distribution is illuminated by coherent light. The scattered light from the micro-particles (called object wave) interferes with the unscattered light (called reference wave) and creates a hologram of the 3D micro-particle field distribution. The holograms are recorded directly in digital form using the CCD. The study of the micro-particles size, shape and 3D distribution can be performed using the numerical reconstruction methods described in the previous chapter. The size of the particle can be measured by calculating the number of pixels

containing the particles image at the corresponding reconstruction plane. The reconstructed image shows the projected shape of the object normal to the illumination direction during hologram recording. Numerical reconstruction of holograms can be performed at different reconstruction planes, which provide the entire 3D volume analysis using only a single hologram. The block diagram of digital holography for particles imaging and metrology is shown in Figure 4.1.

Figure 4.1. Digital micro-particle holographic methodology

Digital micro-particle holographic imaging system provides an aperture limited numerical resolution for a volume. The lateral resolution is provided by the pixel size of the reconstruction image, that depends on the recording geometry and CCD pixel size. The sampling of the holographic fringe during digitization of the hologram provides the quality of the laterally reconstructed images. The depth resolution in digital holography is rather poor. This is because the depth of focus depends on the aperture of the optical system which is given by the size of the CCD as well as the particle size. To overcome this limitation, the LDHM system has been presented for 3D imaging applications.

Various optical geometries have been presented for particles analysis using digital holography [111,113-114]. The simplest and most common optical system for particles analysis is using a collimating laser beam to illuminate the particle field. The limitation of such geometry is the poor resolution of the CCD, that restricts the size of particles to be measured. Two approaches are used to achieve magnification; first using a microscopic objective (MO) [125], and the second called the lensless microscopy as discussed in Chapter 3. Digital particle holography using collimated wave and using lensless microscopic system are discussed and evaluated.

- Using collimated laser beam

The optical system is shown in Figure 4.2. A collimated laser beam illuminates the particle field, and the hologram i.e. interference between the directly transmitted light and the light diffracted by the particles is recorded by using a CCD sensor.

Figure 4.2. In-line digital particle holography using collimated light

Let (x, y) be the object plane and (ξ, η) the hologram plane. The object wave $O(\xi, \eta)$ at the hologram plane is defined as the convolution of amplitude transmittance of the

particle $A_o(x, y)$ with the impulse response of the coherent optical system and can be written as

$$O(\xi, \eta) = \frac{\exp(ikd)}{i\lambda d} \iint A_o(x, y) \exp\left[\frac{ik}{2d}\{(\xi - x)^2 + (\eta - y)^2\}\right] dx dy \quad (4.1)$$

where $k = 2\pi / \lambda$, is the wave number and d is recording distance. For different particles $O(\xi, \eta)$ is different because of their different amplitude transmittance or size.

The interference between the object wave $O(\xi, \eta)$ and plane reference wave $R(\xi, \eta)$ is recorded at the hologram plane (ξ, η) . The complex amplitude of the interference pattern at the hologram plane is,

$$U_1(\xi, \eta) = O(\xi, \eta) + R(\xi, \eta) \quad (4.2)$$

The CCD records this interference pattern in the form of intensity distribution $H(\xi, \eta) = U_1(\xi, \eta)U_1^*(\xi, \eta)$, called digital hologram which is stored in the computer. Thus,

$$H(\xi, \eta) = |O(\xi, \eta)|^2 + |R(\xi, \eta)|^2 + O(\xi, \eta)R^*(\xi, \eta) + O^*(\xi, \eta)R(\xi, \eta) \quad (4.3)$$

A digitally recorded hologram of micro-particles in 3D is shown in Figure 4.3. A $0.532\mu m$ frequency doubled diverging Nd-YAG laser beam was used to illuminate a 4-mm thick glass slide, which had few micro-particles about $\sim 15\mu m$ in diameter on either face. The Fresnel hologram was recorded on a CCD placed at distances of 64mm and 68mm from the faces of the slide. The CCD had 1280 x 720 square pixels, 6 μm in size.

In the reconstruction step, the hologram is multiplied by a reconstruction wave (R_1) and the reconstructed complex wave field at a distance d' is obtained using the Fresnel's diffraction integral. The numerical reconstruction process was performed using convolution method (CV). The reconstructed wave field can be written as,

$$U(x, y, d') = \{H(\xi, \eta)R_1(\xi, \eta)\} \otimes \{g(\xi, \eta)\} \quad (4.4)$$

where $g(\xi, \eta)$ is the impulse response of coherent optical system at distance d' .

Figure 4.3. Digital in-line particle hologram

To reconstruct the real image of the particles, the reconstruction wave should be an exact replica of the complex conjugate of the reference wave ($R_1 = R^*$). Figures 4.4 (a) and (b) show the amplitude images at reconstruction distances $64mm$ and $68mm$ using the CV method. In the reconstructed image the bright background is because of the direct wave, and the out of focus images of particles appear as hollow circles in the reconstructed images. Since the pixel size of the reconstructed image remains constant with

reconstruction distance and equal to the pixel size of the CCD, so the size and position of the objects can be determined by the numerically reconstructed images.

Figure 4.4. Amplitude images of particles at different planes

Depth of focus:

The small interference angle between object and reference waves decreases the numerical aperture (NA) in digital holography. The NA in digital holography of particles with collimated wave is usually less than 0.1 because of small interference angle [116]. This leads to a large depth of focus during reconstruction. A plot of depth of focus for

different particle size for collimating wave with $\lambda = 0.532\mu m$ is given in the Figure 4.5.

For particles study using collimating wave recording, the depth of focus is [123],

$$\Delta z \sim \frac{d^2}{\lambda} \quad (4.5)$$

where d is particle size and λ is the wavelength. Clearly, the quadratic dependence on the particle size makes the resolution of large particles problematic. The requirement is to identify the exact depth location of particles, and the depth resolution is decreases with increase in particles size. For the same size of particles study in volume, the location of particle can be identified accurately by using the plot of reconstructed amplitudes along depth values.

Figure 4.5. Depth of focus for in-line digital particle holography with collimated light for different particle size

4.1.2 Particles location and size measurement methodology

Numerical reconstruction methods in digital holography are most suitable for quantitative measurements of particle position and size in space. In order to measure the position of particle in 3D, the average intensity of pixels containing the particle image is studied at the different depths. The maximum intensity at the corresponding depth defines the accurate depth of the particle. At the accurate depth position the amplitude image of particle is sharpest and this image can be used to calculate the size of the particle, by counting the number of pixels representing the amplitude images.

Particles ($28\mu m$ average diameter) are studied with digital in-line holography. The particles are placed in a glass slide, and a digital hologram is recorded using the CCD containing 1028×960 pixels with pixel size $4.65\mu m$. The wavelength of the light used $0.405\mu m$. The digitally sampled hologram is shown in Figure 4.6.

Figure 4.6. Digitally sampled hologram

Numerical reconstruction process is performed using the collimated reference wave and convolution method as shown in Figure 4.7.

In order to suppress zero-order term the subtraction of the reference wave has been performed before hologram reconstruction process. After selecting the intensity threshold value of the reconstructed image, the contrast of the reconstructed image can be improved and shown in Figure 4.8. The reconstructed particle image light intensity around the centre of the reconstructed image is much larger than the light intensity on the background. The threshold value is selected to minimize the background intensity and thus it improves the contrast of image.

Figure 4.7. Amplitude image reconstruction without zero-order subtraction

Two particles are selected to depth measurements, named particle 1 and particle 2, as shown in Figure 4.8. In order to get particle position in depth, the average intensity of

6×6 pixels is plotted for a depth range. These results are separately computed from the hologram for each particle. Figure 4.9 (a) and (b) shows the intensity value of the particles 1 and 2 corresponding to the different depth values. The reconstructed light intensity becomes the highest around the z-coordinate at the exact depth location of corresponding particle. The depth resolution of the measurements is depend on the system NA as discussed previously.

Figure 4.8. Amplitude image reconstruction with zero-order subtraction

Figure 4.9. Depth profile of reconstructed image for (a) particle 1, and (b) particle 2

Once detecting the depth location of the particles, the next step is to measure their sizes. To measure the size of the particles, the two dimensional reconstructed image of the particle only at its exact depth location is studied. The shade of the bright part measures the diameter of the local particle in the reconstructed image. This measurement is performed by plotting the reconstructed intensity along X and Y directions of the particle image at the focus plane. Figures 4.10 (a) and (b) shows the intensity of the particle 1 corresponding to the two perpendicular directions (X and Y). Since the CV method of reconstruction has been used thus the one pixel size of the reconstructed image is equal to the pixel size of CCD. Thus in order to measure the particles size, the requirement is to calculate the number of pixels representing the particles image. The number of pixels can be counted using the peak of profile, thus the size of particles can be calculated as

$$\text{Particle size} = \text{No. of pixels} \times \text{pixel size} \quad (4.6)$$

The number of pixel along and X and Y direction is 6 to represent the particle image, which provides the size of particle $27.9\mu\text{m}$.

Figure 4.10. Intensity plot in X and Y directions of the focused image for (a) particle 1, and (b) particle 2

4.1.3 System comparison with conventional microscope

In order to compare the particles depth location and size measurements, the digital particle holographic system has been compared with conventional optical microscopic system using polymer micro-spheres stuck on a thin glass side. The optical microscopic image of the distribution of the particles on the slide is shown in Figure 4.11 (a). Digital in-line hologram of same particles field distribution is recorded, the numerical reconstructed amplitude image of the particle field is shown in Figure 4.11 (b).

Figure 4.11. Comparison of optical and digital holographic images for particle field distribution (a) Optical microscopic image, (b) Digital holographic amplitude image

The effect of out-of-focus twin image appears as circular fringes which do not effect the image. The amplitude image by digital particle holography shows a nice comparison with optical microscopic image.

- Reconstruction in 3D

To show the capability of digital holography for 3D imaging of micro-particles, two thin glass slides are placed $440\mu m$ apart and particles are placed on both the slides as shown

in Figure 4.12. The optical microscopic images of the particles at both the slides are shown in Figure 4.13, for that two images are recorded by mechanically focusing the microscopic objective at each slide.

Figure 4.12. Micro-particles placed in two different planes

Figure 4.13. Optical microscopic images of micro-particles on (a) slide-1, and (b) slide-2

The slides are illuminated by the laser light and hologram is recorded using the CCD sensor. This recorded hologram contains all the information that required to reconstruct the whole 3D image of particles. The numerically focused images at the two planes from the same hologram are shown in Figure 4.14. The advantage with digital holography is the need for single hologram that can provide all 3D section of the particles images. It can be clearly seen that all the particles that are visible in the optical microscopic images are clearly resolved in numerical reconstruction. Thus single hologram provides the high resolution images of particles in whole 3D volume.

Figure 4.14. Numerically reconstructed images on particles (a) first slide, and (b) second slide

4.1.4 Sectioning of amplitude images

In 3D imaging, the effect of out-of-focus particles degrades the quality of image of focused particles as shown in Figure 4.14. An approach to eliminate this effect and to slice in-focus particles in digital holography for the analysis of micro-particles in 3D is developed. In addition the effects of background illumination by zero order wave and twin image are simultaneously removed.

As discussed before, the small angle in in-line digital holography for 3D micro particles analysis gives rise to three problems during the reconstruction process: overlap of the object wave and the un-diffracted zero order wave; overlap of the real and virtual images and finally appearance of the defocused images of object outside the plane of reconstruction. The first two effects have been resolved using various image processing methods as discussed in article 3.1.2, and are usually not a major problem for digital

particle holography. However the third effect has not been addressed so far and thus the full capability of holography has not been exploited.

At the focus distance of particle image, the amplitude of the real image wavefront is a maximum. However contributions from the reference wave and the conjugate image wave degrade the quality of the reconstructed image. In addition to a 3D distribution of particles, the defocused images of particles lying outside the focus plane also appear in the final reconstructed image. A method based on the subtraction of reconstructed wavefronts is given here to eliminate the defocused particles and display a slice containing only the in-focus parts of the image. Furthermore, only a single hologram is necessary and no other processing is required. The bright background due to zero order term is also simultaneously minimized and although the twin image is not a major problem for small particles, its effect can be reduced as well.

Figure 4.15. Reconstruction geometry for particles image sectioning

In the current approach the property that only the in-focus reconstructed image wave is a real quantity, is used to minimise the out-of-focus and other terms effects and thus provide an image section with only the focused parts of the object visible. The depth of focus of the system limits the isolation of the section. The depth of focus depends on the NA that is related to the particle size and is typically large because of the small NA in DH.

The reconstruction geometry of subtraction methodology is shown in Figure 4.15. At the focus plane of one set of particles, let U_I^* and U_I represent the real and conjugate image waves due to in-focus particles respectively, U_{II}^* and U_{II} are the real and conjugate image waves due to out of focus objects and U_D is the direct wave (zero order term). Since the amplitude of U_I^* is a maximum at the focal plane then the amplitude of reconstructed complex wave fields at in-focus plane (reconstruction distance d) and at a reconstruction distance $(d + \Delta d)$ can be written as

$$|U(x, y, d)| = |(U_I^*)|_{\max} + |U_{II}^*| + |U_{I+II}| + |U_D| \quad (4.7)$$

$$|U(x, y, d + \Delta d)| = |U_I^*| + |U_{II}^*| + |U_{I+II}| + |U_D|$$

U_{I+II} is the sum of conjugate image waves due to object (U_I) and all other out-of-focus objects (U_{II}) which for small particles can be ignored. The sum of the amplitudes of conjugate image waves (U_{I+II}) and zero order wave (U_D) creates a constant background noise in the final reconstructed image. It is seen from amplitude profile of reconstructed wavefield that the amplitude of the in-focus particle changes drastically as one moves away from the point of best focus (Figure 4.9). However for particles that are out-of

focus at this plane, their amplitude is a slowly varying function [116]. The simultaneous presence of the constant term ($U_{I+II} + U_D$) results in a constant background noise and degrades the reconstructed image quality. Thus the subtraction of the amplitudes at the focus plane and out of focus plane will only show the reconstructed amplitude of the focused particles at reconstruction distance d . Hence the subtraction of $|U(x, y, d)|$ and $|U(x, y, d + \Delta d)|$ gives a non-zero value only for in-focus particles while the amplitudes of the defocused particles and the direct and other background waves are eliminated.

To demonstrate this theoretical analysis, Reconstructed images shown in Figures 4.4 (a) and (b) are used for image slicing. The choice of subtraction distances (Δd) is limited on the one hand by the depth of focus and on the other hand by the effect of the conjugate image and influence from other waves. For the current set-up the subtraction distances (Δd) is equivalent to depth of focus of particles and the best effect is observed are $0.7mm$ and $1.1mm$ for front and backside of glass plate respectively.

Figures 4.16(a) and (b) shows the corresponding subtracted images for front and backsides of glass plate. The images used for subtraction were reconstructed at $63.3mm$ and $66.9mm$ respectively. It is clear that the direct beam, the conjugate image and the out-of-focus images are eliminated and only the in-focus particles are visible. In addition, certain smaller particles not visible in the earlier image appear in this image. Also large objects are not completely eliminated as their depth of focus is large and hence they also appear in the subtracted image. Furthermore, what appears as single particle in the

original reconstructed hologram are indeed two particles. Thus the subtraction approach allows each section of the hologram to be viewed with more clarity.

Figure 4.16. Subtracted images of particles in two different planes

4.2 Lensless microscopic system for micro-particles analysis

Particles analysis using collimated wave digital holography is limited to the study of large particles. The pixel size of available CCD restricts the resolution of the system, and limited numerical aperture causes the poor depth resolution. To improve the in-line digital holographic system capability, LDHM system is explored for micro-particles analysis.

4.2.1 LDHM system capability

Micro-particles imaging in 3D is performed using the LDHM system. The capability of the system is explored for the measurement of location and size of micro-particles in 3D. Copolymer micro-spheres, $9.6\ \mu m$ in diameter have been studied using LDHM. The particles were flowing in water and placed inside a cuvet $10mm \times 10mm \times 100mm$. The experimental arrangement is shown in Figure 4.17. A $0.405\ \mu m$ laser beam is focused on a $1\ \mu m$ size pinhole, and the sample is placed in the path of the diverging beam coming from the pinhole. The hologram of the particle system is recorded with the CCD having the array size 1280×960 of pixels with size $4.65\ \mu m \times 4.65\ \mu m$. The CCD is placed at a distance of $35mm$ from the pinhole. The sample is placed in the path of the diverging beam and the pinhole to sample distance controls the magnification of the system.

The recorded hologram is saved in the computer and numerical reconstruction process is performed using the converging reference wave as discussed in article 3.2.1. The reconstructed amplitude images of the particles field at distance $22.55mm$ and $23.10mm$, from the hologram plane are shown in Figures 4.18 (a) and (b). For reconstruction

process, the preprocessing of hologram is performed by subtracting the reference wave (without sample) from the hologram. This kind of preprocessing is used to suppress the zero order term. The use of highly diverging wave improves the system resolution in 3D as discussed in Chapter 3.

Figure 4.17. Experimental arrangement of transmission LDHM

Figure 4.18. Reconstructed intensity showing micro-particle field distribution in different planes (a) 22.55mm, and (b) 23.10mm from CCD to reconstructed image planes

- Particle depth measurement

The accurate depth localization of the particles in 3D space can be identified by using the average intensity value of the pixels displaying the particle amplitude image. At the position where the intensity value becomes maximum represents the particle position in 3D. The average intensity depth profile of encircled particle showing in Figure 4.18(a), is shown in Figure 4.19. The depth of focus of the system depends on the system NA, and is defined by the formula in Equation (3.13). In the present experiment, for $9.6\ \mu\text{m}$ size particles the intensity peak is found in the depth range of $50\ \mu\text{m}$ and thus shows the depth resolution to be roughly 5 times the particles diameter.

Figure 4.19. Average intensity of particle along reconstruction depth

- Particle size measurement

To determine the size of the particles, the intensity value of the reconstructing pixels, can be used for measurements along X and Y directions. The particle shown in Figure 4.18 (a) is considered for the size measurement, the reconstructing pixels of the particle is

shown in Figure 4.20 (a). The intensity profile along X and Y direction are shown in Figures 4.20(b) and (c) respectively.

Figure 4.20. (a) Reconstructed pixels of particle, and intensity profile of the particle along (b) x-direction, and (c) y-direction

The size of particle can be identified by counting the number of pixels from the intensity peak and multiplied by the effective pixel size as

$$\text{Particle size} = \text{No. of pixels} \times \text{effective pixel size} \quad (4.8)$$

The effective pixel size is calculated because of the demagnification effect of the converging reconstruction wave at the reconstructed image plane and the use of FT method of reconstruction. The demagnification effect and FT method of reconstruction is depends on the reconstruction distance. Thus the effective pixel size is different corresponding to the different depth locations.

Reconstruction of pre-processed hologram, the particle image light intensity around the centre of the reconstructed image is much larger than the background light intensity, and it suddenly decreases around the radial distance corresponding to the given true diameter

of the particle. The particle radius can be accurately detected with an appropriate cut-off for intensity. The cut-off value is selected in such a way that the background intensity minimize (ideally it is zero). The cut-off value is 35% of reconstructed intensity. If the cut-off value is increase, it reduces the number of pixels representing the particles image. For higher cut-off values, the effect of one less pixel of particle image would imply an error about 16%.

Table 4.1. Particle size measurement using LDHM system

Optical system parameters	Reconstructi on Depth (mm)	Effective pixel size μm	Number of pixels	Measured average particle size (μm)	Measure-ment error (%)
$\lambda = 0.405 \mu m$ $D = 35mm$ $\Delta\xi = \Delta\eta = 4.65 \mu m$	22.55	X=1.33	X=7	9.3 ± 1.33	3.1
		Y=1.77	Y=6	10.6 ± 1.77	10.4

4.2.2 System analysis and improvements

In LDHM, intensity of reconstructed particles is used for depth and size measurements. For reconstruction using the converging reference wave, the size of the reconstructed images is different for different reconstruction distances. The size becomes smaller for the reconstruction planes far from the hologram plane. So the reconstructed image is shrinking down with increasing reconstruction distance. This effect significantly changes the imaging properties for LDHM, particularly for higher magnification. Thus for micro-

particles imaging, the behavior of depth profile of the particles at spatial location (axial and non-axial location), should not be exactly same. In order to achieve the correct behavior of depth profile of non-axis particles, it is required to make sure that, the spatial positions of the reconstructed pixels should not change with the reconstruction distance.

Consider the reconstructed particles image as shown in Figure 4.21 (represent a section of full reconstructed image). Here the hologram is recorded with the same set-up as shown in Figure 4.17, the intensity image is showing the reconstructed particles distribution at the reconstruction distance 22.3mm . In the image, the particle 1 is located on the optical axis and particle 2 is located away from the axis. The plots of the depth profile for these particles are shown in Figures 4.22 (a) and (b) respectively.

Figure 4.21. Reconstructed particles image and selecting particles for depth analysis

Figure 4.22. Depth intensity profile of particles (a) near to optical axis, and (b) far from the optical axis

It can be clearly seen in Figure 4.22 that the depth profile of axial and non-axial particles are not the same. In the intensity plots, the depth resolution of particle 2 is about double of particle 1. This difference is because, the shifting of the pixels representing the reconstructed image with the reconstruction depth.

Figure 4.23. Pixels reconstruction for different depths corresponding to the particle 1

Figure 4.24. Pixels reconstruction for different depths corresponding to the particle 2

The shifting in pixel position is explored by identifying the spatial location of the reconstructed pixels at different depths. Figure 4.23 shows reconstructed images of a 28×28 pixel region with the reconstructed particle 1 at the centre. The bright pixels show the particles image at different depths. Since the particle is on the optical axis, the pixels position does not shift with reconstruction distance.

The reconstructed pixels of the particle 2 at different depths are shown in Figure 4.24. The shifting of the particles can be clearly observed as reconstruction distance increases. It causes the deviation in the depth profile of the particles located at different spatial positions and may creates the inaccuracy in the depth measurements.

The shift in pixel positions of particle with change in reconstruction distances need to be control for accurate depth measurement. This shift can be controlled by using the zero-

padding of hologram as proposed in Equation (3.15). The effects of zero-padding of holograms are shown in Figures 4.25 and 4.26. The images show the reconstructed pixels of the particle 1 and 2, corresponding to the same depth positions as shown in Figures 4.23 and 4.24 respectively.

Figure 4.25. Modified pixel reconstruction at different depths for the particle 1

Figure 4.26. Modified pixel reconstruction at different depths for the particle 2

The shifting of the pixels is controlled, especially for the case of particle 2. The depth profile of the particle 2 using zero-padding approach is shown in Figure 4.27. The improvement in the profile can be clearly observed, and provides the similar depth resolution as for on-axis particle (Figure 4.22(a)). However there is no change in the depth profile for the particle 1, and it is also expected because of no shift in pixels with depths.

Figure 4.27. Modified depth profile of off-axis particle

4.3 Methodology for dynamic analysis of micro-particles

To study the particles flowing in any fluid or gas medium, first a sequence of holograms need to be recorded corresponding to the dynamic changes. The reconstruction process is then performed, to analyze the particles field. One simple method is to reconstruct the holograms at different depths and visualize the particles behavior corresponding to the different frames. Two different methodologies are presented here for the study of dynamic micro-particles analysis. The experiment is performed with polymer microspheres flowing in water. The holograms are recorded at 1 second increment using the CCD sensor and then analyzed to track particles in 3D.

4.3.1 Dynamic analysis in 3D by holograms addition

In this method, the recorded holograms are added first and then reconstruction process is performed. The dynamic behavior of particles can be studied during the reconstruction of the final hologram (addition of holograms). To explain this method, an experiment using LDHM set-up is performed using the laser beam ($\lambda = 0.405\mu m$) passing through a $1\mu m$ size pinhole. The CCD is placed at distance of $37mm$ from the pinhole. The copolymer micro-spheres are flowing in the cuvet placed between the pinhole and CCD (Figure 4.17). Three separate holograms are recorded with one second interval during the motion of micro-spheres. The reconstructed images corresponding to each hologram are shown in Figures 4.28 (a), (b) and (c) respectively (reconstruction distance $21.79mm$). The two of the micro-spheres can be seen and their positions changes in each frame representing the motion of the particles.

Figure 4.28. Reconstruction of moving particles in a plane

The three recorded holograms are added before reconstruction. The reconstruction is then performed using the same parameters as above. The reconstructed image, of the addition of holograms, is shown in Figure 4.29. The reconstructed particles image can be seen in a

single reconstructed frame. The dynamic behavior of the particles motion can be seen in the single reconstructed image.

Figure 4.29. Addition of holograms prior to reconstruction provides motion in single reconstruction frame

Hence, addition of holograms prior to reconstruction can also provide the whole 3D field reconstruction of moving particles. Further evidence is shown in Figure 4.30, where three holograms of the particles in 3D are recorded and added using the same recording parameters as before. The reconstruction at 4 different planes are shown in Figures 4.30(a)-(d), corresponding to reconstruction distances of 19.43mm , 20.83mm , 21.45mm , and 21.56mm respectively. The reconstruction depth stated to two-decimal point because the depth resolution of LDHM system is higher and provides the depth accuracy of about $50\mu\text{m}$ for $9.6\mu\text{m}$ size particles during numerical reconstruction process. The in-focus set of particles in the corresponding plane are highlighted. The displacement between particle's pixel positions can be used to study the velocity component in the

corresponding plane as given in Table 4.2. The displacement components of particles at their corresponding focal planes show the flow behavior of particles in different planes. It can be clearly seen that the particle reconstructed at larger depth flowing with larger velocity compare to the particles reconstructed at smaller depth from CCD. Thus it provides the exact dynamic behavior of particles in different planes (parallel to the CCD sensor planes) flowing in the cuvet.

Figure 4.30. 3D dynamic particles analysis by addition of holograms (a) 19.43mm (b) 20.83mm (c) 21.45mm (d) 21.56mm

The noise level by hologram addition becomes higher and comes as speckle-like texture which may be mistaken a particle. The background noise level also depends on the medium contains particles. Thus hologram addition methodology is not suitable for such case. This limitation has been addressed in article 4.3.2 using the sequence of hologram and intensity threshold method.

Table 4.2. Velocity measurements of particles moving in different depth

Depth position of particles from CCD (mm)	Average velocity of particles along Y- direction ($\mu\text{m} / \text{Sec}$)
19.43	22.1
20.83	54.4
21.45	68.8
21.56	72.2

4.3.2 Dynamic displaying using intensity threshold methodology

The main disadvantage with addition of holograms prior to reconstruction is the increase in the random noise in the reconstructed images. The noise level increases with increasing number of holograms used for addition. Thus for a large number of holograms or higher particle density the noise increases significantly, and thus the method does not work properly.

The method, based on reconstructed intensity threshold, is explored for dynamic analysis of micro-particles. This method is suitable for the study of larger number of holograms. The methodology for dynamic 3D analysis the particles has been developed in MATLAB environment. The following algorithm steps were used:

- (i) Reading of the number of frames for reconstruction.
- (ii) Subtract the reference beam from each frame and set the reconstruction parameters.
- (iii) Selected reconstruction depth range and divide into number of steps.
- (iv) Perform zero-padding of holograms, to avoid shifting of the pixels of off-axis particles.
- (v) Calculate the particles intensity, and select a threshold for the fully reconstructed image intensity. All intensity values higher than threshold is consider as the particle.
- (vi) Do reconstruction for depth steps and find the exact position of each particle. The particles depth position is calculated at which the average intensity of pixels become maximum.
- (vii) Calculate the number of identified particles corresponding to each frame.
- (viii) Display the reconstruction of each frame corresponding to all reconstruction distances.
- (ix) Display the particles position in XY, YZ and in 3D.

- Experimental Results

An experimental investigation has been performed using the same holograms as shown in Figure 4.28. The reconstruction depth range was from $21.7mm$ to $21.8mm$, in steps of $10\mu m$. The reconstructed images following the algorithm above, was displayed as shown in Figure 4.32. This shows not only the reconstructed particles from the hologram but also their position in the XY, YZ or 3D plane. In Figure 4.31 (a), the upper left side shows the reconstructed intensity image at the distance $21.79mm$ (also for Figures 4.31(b) and (c)). The pixel locations in XY plane of reconstructed particles are displayed on the

upper right side of the image. As discussed before, to find the exact depth position of the particles, first the average intensity of the pixels are calculated at each reconstruction distance, the position of maxima provides depth location. The right side of Figure 4.31 (b) displays the depth (Z value) and the Y position of the particles. Finally the 3D display of the particles are shown in Figure 4.31 (c).

Figure 4.31. Visualization of dynamic micro-particles during 3D reconstruction, identified particles in (a) XY plane, (b) YZ plane, and (c) 3D displaying

The dynamic analysis of co-polymer micro-spheres ($9.6 \mu m$) in 3D is further analyzed. The micro-spheres are flowing in distilled water. The LDHM system as shown in Figure 4.17 has been used to record holograms. The distance from the pinhole to CCD was $35mm$. Five holograms were recorded, at intervals of one second. The behavior of the particles in $1mm$ depth of $10mm$ size cuvet was analyzed, with the reconstruction step of $20\mu m$. The results are shown in Figures 4.32, 4.33 and 4.34. Figure 4.32 shows the movement of particles in the XY plane, corresponding to each frame (a)-(f). Only in-focus particles are shown. The number of identified particles in a reconstructed depth range can also be identified. To find the depth of each particle, the results of Z location corresponding to the Y position is shown in Figures 4.33 (a)-(f). The predicted motions of the particles are shown as lines in the direction of particles movement.

Figure 4.32. XY plot of six frames of particles during motion

Figure 4.33. YZ plot of six frames of particles during motion

Figure 4.34. 3D plot of six frames of particles during motion

The 3D reconstruction of the holograms is finally shown in Figure 4.34. This plot provides the better visualization of dynamic motion of particles in 3D. The location of each particle, its depth and dynamic behavior can be clearly observed. A microscopic or a PIV system will not be capable of providing these images. The 3D velocity components of 4 particles (selected and shown in Figure 4.32 (a)) are studied and presented in Table 4.3. This analysis is useful to see the 3D dynamic behaviors of particles and can be used to predict the motion of particles in 3D.

Table 4.3. 3D dynamic behavior analysis of micro-particles using LDHM system

Frame No.	Particle 1						Particle 2					
	3D coordinate			Velocity component between alternative frames ($\mu\text{m}/\text{Sec}$)			3D coordinate			Velocity component between alternative frames ($\mu\text{m}/\text{Sec}$)		
	X Pixel	Y Pixel	Z location (mm)	X	Y	Z	X Pixel	Y Pixel	Z location (mm)	X	Y	Z
1	77	233	19.6	-	-	-	220	350	19.38	-	-	-
2	75	248	19.58	2.6	25.8	20	219	358	19.32	1.3	13.8	60
3	74	263	19.56	1.3	25.8	20	219	365	19.3	0	12.12	20
4	72	277	19.54	2.6	20.1	20	217	378	19.3	2.6	22.4	0
5	70	288	19.52	2.6	18.9	20	216	390	19.28	1.3	20.6	20
6	68	305	19.5	2.6	29.2	20	215	405	19.26	1.3	25.8	20
Frame No.	Particle 3						Particle 4					
	3D coordinate			Velocity component between alternative frames ($\mu\text{m}/\text{Sec}$)			3D coordinate			Velocity component between alternative frames ($\mu\text{m}/\text{Sec}$)		
	X Pixel	Y Pixel	Z location (mm)	X	Y	Z	X Pixel	Y Pixel	Z location (mm)	X	Y	Z
1	236	338	19.36	-	-	-	465	58	19.96	-	-	-
2	234	345	19.34	2.6	12.1	20	464	76	19.9	1.3	30.9	60
3	233	356	19.34	1.3	18.9	0	463	103	19.9	1.3	46.4	0
4	232	364	19.32	1.3	15.5	20	462	124	19.9	1.3	36.1	0
5	230	375	19.3	2.6	18.9	20	461	140	19.88	1.3	27.5	20
6	228	384	19.24	2.6	15.5	60	460	158	19.84	1.3	30.9	40

4.4 Chapter summary

The capability of in-line digital transmission holography is explored for micro particle visualization and tracking. The methodology of particle depth and size measurement using collimated laser beam is studied. A method of sectioning of particles using the amplitude image in 3D is explored, without any pre-processing of holograms. The LDHM system is explored for micro-particles analysis, which is able to resolve the problems of poor lateral and depth resolution using collimated wave. The advancement of LDHM setup is explored and presented for dynamic analysis. Techniques of tracking of dynamic micro-particles were studied. The methodology for 3D dynamic analysis is developed with better dynamic visualization and tracking.

CHAPTER 5

DIGITAL DYNAMIC HOLOGRAPHIC INTERFEROMETRY SYSTEM DEVELOPMENT

Dynamic measurements using digital holographic interferometry are discussed in this chapter. Characteristic functions for different types of motions are studied, which is useful to define the object wave in digital holography. The methodology of time averaged in-line digital holographic interferometry is developed for vibration analysis. A novel double exposure method is developed, which is most suitable for vibration measurements, and also can simultaneously suppress the background noise in an in-line geometry. The analysis of reconstructed amplitude and phase information from time averaged holograms are discussed. It is shown that the numerical reconstructed amplitude and phase information represent the vibration and mean static deformation information respectively. For diverging object wave, the effect of magnification on the reconstructed amplitude and phase information are presented. It is shown that the amplitude and phase information shows the contrary behavior with the change in the magnification.

5.1 Digital dynamic holographic interferometry

Digital dynamic holographic interferometry is different from static digital holographic interferometry in that both the amplitude as well as the phase difference of the two holograms recorded at two different states provides imaging characteristics of dynamic phenomenon. For vibration measurements, time averaged digital hologram is used to

record dynamic behaviors of periodically vibrating objects. This is not suitable for transitional phenomenon wherein traditional double exposure holographic interferometry can be adopted using a high-speed camera.

5.1.1 Characteristic function of measurements

Digital holographic interferometry is applied for the analysis of any object deformed either statically or dynamically. The object wave corresponding to the particular motion can be defined by the characteristic function of that particular motion.

Let $\Delta\phi$ be the phase change by the displacement of the object. Let $f(t)$ is a function of time and is defined by the type of motion of the object. The characteristic function M_T , can be defined by the time average integral as [136],

$$M_T(\Delta\phi) = \frac{1}{T} \int_0^T e^{i\{\Delta\phi \cdot f(t)\}} dt \quad (5.1)$$

where T is the exposure time.

Figure 5.1. Observation geometry of deformation measurement

A typical geometry of the object deformation with illumination and observation direction is shown in the Figure 5.1. Let $\vec{k}_1$ and $\vec{k}_2$ be the propagation vectors of light illuminating the object point P and the light scattered towards the observation point O (hologram plane) respectively, then the sensitivity vector for this geometry is defined as

$$\vec{K} \equiv \vec{k}_1 - \vec{k}_2 \quad (5.2)$$

Let P' be the point after a displacement $\vec{d}$ then phase difference between the deformed and undeformed state is,

$$\Delta\phi = \vec{K} \bullet \vec{d} = Kd(\cos\theta_i + \cos\theta_o) \quad (5.3)$$

Where θ_i and θ_o are the angle illumination and observation respectively. The term $(\cos\theta_i + \cos\theta_o)$ is called geometrical factor represented by g' . Thus characteristic function written as,

$$M_T(\Delta\phi) = \frac{1}{T} \int_0^T e^{i\{(\vec{K} \bullet \vec{d}) \cdot f(t)\}} dt \quad (5.4)$$

Characteristics functions can be evaluated for a variety of motions and are summarized for various separable, single time functions in Table 5.1.

It is observed that fringes in double exposure interferometry ($\cos^2$ fringes) have uniform brightness for all orders of interference, while all other motions represents decreasing fringe brightness with increasing amplitudes.

Table 5.1. Characteristic functions of measurements

Type of motion	Time function $f(t)$	Characteristic function $ M_T(\vec{K} \bullet \vec{d}) ^2$
Static displacement (double-exposure)	$f(t) = 0, 0 \leq t < \frac{T}{2}$ $f(t) = 1, \frac{T}{2} \leq t \leq T$	$ M_T ^2 = \cos^2(\frac{1}{2} \vec{K} \bullet \vec{d})$
Harmonic vibration	$f(t) = \cos \omega t$	$ M_T ^2 = J_0^2(\vec{K} \bullet \vec{d})$
Constant velocity	$f(t) = \frac{t}{T}$	$ M_T ^2 = \frac{\sin^2(\frac{1}{2} \vec{K} \bullet \vec{d})}{(\frac{1}{2} \vec{K} \bullet \vec{d})^2}$
Constant acceleration (start from rest)	$f(t) = \left(\frac{t}{T}\right)^2$	$ M_T ^2 = \frac{C^2(\sqrt{\vec{K} \bullet \vec{d}}) + S^2(\sqrt{\vec{K} \bullet \vec{d}})}{\frac{2}{\pi}(\sqrt{\vec{K} \bullet \vec{d}})}$ (C and S are the Fresnel integrals)
Exponentially damped harmonic vibration	$f(t) = e^{-\beta t} \sin \omega t$ (β - damping factor)	Characteristic function not defined (Graphically presented)

5.1.2 Dynamic interferometric measurements

The instantaneous dynamic deformation of any object can be measured using the pulsed digital holography, in this digital holograms are recorded corresponding to the different pulse of the laser beam and their subtraction provides the dynamic changes. The alternative approach is using the high speed CCD cameras for hologram recording. For vibration analysis of the objects, time average holography can be used and explored here.

5.2 Time-averaged in-line digital holographic interferometry

Powell and Stetson first explained the principle of time averaged holographic interferometry for vibration analysis [7]. For time averaged recording of a vibrating object, the exposure time must be larger than the period of vibration. In this case, it can be shown that the amplitude distribution of the object is modulated by the zero order Bessel function J_0 . Time averaged off-axis digital holography was demonstrated by P. Picart et al [101], who showed that the numerically reconstructed object is modulated by the J_0 fringes as in conventional time average holography. The digital holographic time averaged methods used so far, either uses the off axis geometry or quasi Fourier set-up and only suitable for relatively larger objects. In this chapter time averaged in-line digital holography is studied and explored for smaller objects.

5.2.1 Time-averaged recording and reconstruction of in-line holograms

- Recording

For a sinusoidally vibrating object (Figure 5.2 (a)) in the (x, y) plane, the displacement of the object can be given as:

$$\vec{z}(x, y, t) = \vec{z}(x, y) \cos \omega t \quad (5.5)$$

where ω is the angular frequency of vibration and $\vec{z}(x, y)$ is the out-of-plane displacement which can be divided into two part: the mean deformation component($z_o(x, y)$) and the time varying component($z_v(x, y)$) thus can displacements and can be written as,

$$\vec{z}(x, y, t) = \vec{z}_o(x, y) + \vec{z}_v(x, y) \cos \omega t \quad (5.6)$$

Figure 5.2. (a) Sinusoidally vibrating object, (b) Vibrating object with a change in the mean static state (c) Change in the mean static state

The instantaneous object wave, $O'(x, y, t)$ at any instant scattered from the vibrating object is:

$$O'(x, y, t) = O_0(x, y) e^{i\phi_0(x, y)} e^{i[\vec{K} \cdot \vec{z}(x, y, t)]} \quad (5.7)$$

Here $O_0(x, y)$ is the amplitude of the scattered wave, $\vec{K}$ is the sensitivity vector. $\phi_0(x, y)$ is the phase representing the mean deformation state of the vibrating object and is called the mean static state.

For time averaged recording, the frame capture time τ of the recording device should be larger than the period of object vibration. The time averaged object wave thus becomes,

$$O(x, y) = \frac{1}{\tau} \int_0^\tau O'(x, y, t) d\tau \quad (5.8)$$

$$O(x, y) = O_0(x, y) \exp\{i\phi(x, y)\} \times J_0\{\vec{K} \cdot \vec{z}_v(x, y)\} \quad (5.9)$$

Where J_0 is the zero order Bessel function and $\phi(x, y)$ represents the phase of the object wave and contains the information both about mean static deformation and zeros of Bessel function as defined in Equation (5.6),

$$\phi(x, y) = \phi_o(x, y) + \phi_j(x, y) \quad (5.10)$$

where $\phi_o(x, y)$ contains object surface information and can be considered as source of speckle noise for pure time average case, and $\phi_j(x, y)$ is the time averaged phase.

The in-line time average Fresnel time-averaged digital hologram is the interference of time varying object wave with the in-line reference wave R at the CCD plane (ξ, η) , i.e.

$$H(\xi, \eta) = |O(\xi, \eta) + R(\xi, \eta)|^2 \quad (5.11)$$

If the CCD contains $M \times N$ pixels with pixel size $\Delta\xi \times \Delta\eta$, then the digitally sampled hologram can be written as given in Equation (2.2).

- Numerical reconstruction

The reconstruction of hologram is a diffraction process as discussed in Chapter 2. When the same reference wave used to illuminate the hologram, the wavefield reconstructed at the distance d' at the image plane (x', y') is obtained by diffraction integral as given in Equation (2.8).

The reconstructed wavefield $U(x', y')$ at a distance d' from the hologram plane is obtained by the discrete Fresnel transformation of the digital hologram multiplied by a

numerical reference beam $R(m,n)$ and the impulse response $g(m,n)$ of the coherent optical system. This can be expressed as (Equation (2.11)),

$$U(x', y') = \mathfrak{I}\{H(m,n)R(m,n)g(m,n)\} \quad (5.12)$$

The pixel size of the numerically reconstructed image varies with the reconstruction distance and is given by,

$$\Delta x' = \frac{\lambda d'}{M\Delta\xi}, \quad \Delta y' = \frac{\lambda d'}{N\Delta\eta} \quad (5.13)$$

When the reconstruction distance d' equals the distance d between object and CCD during hologram recording, the real image of the object is formed at the image plane (x', y') .

The amplitude and phase of the numerically reconstructed real image wave is apart from a magnification term, as follows,

$$A(x', y') = |U(x', y')| = O_0(x', y') J_0\{\vec{K} \cdot \vec{z}_v(x', y')\} \quad (5.14)$$

and

$$\phi(x', y') = \arctan \frac{\text{Im}(U(x', y'))}{\text{Re}(U(x', y'))} = \phi_o(x', y') + \phi_J(x', y') \quad (5.15)$$

But because of in-line digital holography, the zero-order wave and the twin image overlap with this real image wave. The reconstructed wave can be written as:

$$U(x', y') = O_0(x', y') e^{i\phi(x', y')} J_0[\vec{K} \cdot \vec{z}(x', y')] + U' \quad (5.16)$$

Here the first term on the right hand side is the reconstructed real image wave and U' is the background noise. This background noise in the final reconstructed real image of the object is due to the zero-order wave and out-of-focus twin image wave, and it does not change with different deformation states of the same object. However, since the speckle pattern changes stochastically between exposures, the background noise may not be exactly equal.

5.2.2 Double exposure method

For in-line geometry, the zero-order and twin image waves overlap with the real image wave. In order to suppress these unwanted waves, a double exposure method is proposed. Here two digital holograms corresponding to different states of the object are recorded and subtracted.

Two time averaged in-line holograms of the object are recorded, one corresponding to the reference state (either static or vibration), and other is the vibration state. Consider an object vibrating at an angular frequency ω at two different amplitudes $\bar{z}_1$ and $\bar{z}_2$ corresponding to the two states. The phase of the mean deformation states are ϕ_1 and ϕ_2 respectively. Then the object wave corresponding to these two states can be written as:

Reference state (either vibrating or static),

$$O_1(x, y, t) = O_0(x, y) e^{i\phi_1(x, y)} e^{i[\vec{K} \cdot \bar{z}_1(x, y, t)]} \quad (5.17a)$$

Vibration state,

$$O_2(x, y, t) = O_0(x, y) e^{i\phi_2(x, y)} e^{i[\vec{K} \cdot \bar{z}_2(x, y, t)]} \quad (5.17b)$$

Time average digital holograms are recorded for these two states of object. On numerical reconstruction, we get the wavefields:

Reference state,

$$U_1(x', y') = O_0(x', y') e^{i\phi_1(x', y')} J_0[\vec{K} \cdot \vec{z}_1(x', y')] + U_1' \quad (5.18a)$$

Vibration state,

$$U_2(x', y') = O_0(x', y') e^{i\phi_2(x', y')} J_0[\vec{K} \cdot \vec{z}_2(x', y')] + U_2' \quad (5.18b)$$

U_1' and U_2' do not change for different deformation of the same object, but are not exactly the same due to variations in the stochastic speckle pattern between the two holograms. This difference also adds to the random noise in the amplitude and the phase term of the reconstructed real image waves. The subtraction of wavefields, ignoring this background noise, can thus be written as:

$$(U_1 - U_2) = O_0(x', y') [e^{i\phi_1(x', y')} J_0\{\vec{K} \cdot \vec{z}_1(x', y')\} - e^{i\phi_2(x', y')} J_0\{\vec{K} \cdot \vec{z}_2(x', y')\}] \quad (5.19)$$

or

$$I = |(U_1 - U_2)|^2 = |O_0(x', y') [e^{i\phi_1(x', y')} J_0\{\vec{K} \cdot \vec{z}_1(x', y')\} - e^{i\phi_2(x', y')} J_0\{\vec{K} \cdot \vec{z}_2(x', y')\}]|^2 \quad (5.20)$$

This wavefield difference and the resulting intensity show the mixing of the mean static deformation fringes and the zero order Bessel fringes due to the time-average recording. Since this mixing is complex and not easy to isolate, the following process is used to separate the Bessel fringes from the deformation fringes.

The amplitude and phase of the individual wavefields are extracted first. The difference in amplitudes then provides the Bessel type vibration fringes while the difference of phase gives the mean deformation as cosine square fringes. These can be represented as:

$$\Delta I = |U_1|^2 - |U_2|^2$$

$$= O_0^2(x', y') [J_0^2\{\vec{K} \cdot \vec{z}_1(x', y')\} - J_0^2\{\vec{K} \cdot \vec{z}_2(x', y')\}] \quad (5.21)$$

$$\Delta\phi = \phi_1(x', y') - \phi_2(x', y') \quad (5.22)$$

Figure 5.3. Double exposure time average in-line digital holographic reconstruction methodology

Thus the unwanted noise by zero-order and twin image wave is automatically suppressed during this subtraction process. Eventually the amplitude subtracted pattern used for the study of vibration amplitude information and phase subtraction provides the information about the mean static deformation of the object during vibration cycle. Figure 5.3 summarizes the reconstruction methodology for the double exposure method used for vibration analysis of the object.

- Experimental analysis

To study the methodology of double exposure method, the vibrations of an aluminum membrane is experimentally studied. The experimental set-up for in-line digital holography used for vibration study is shown in Figure 5.4(a). A frequency doubled Nd-YAG laser operating at $0.532\mu m$ is split into two beams by a variable beam splitter. The object beam is expanded and illuminates the object, while the other is the collimated reference beam. The object, a thin aluminium membrane bonded to a circular metal ring of outer & inner diameters 13 mm & 10 mm respectively (Figure 5.4(b)), is attached to an earphone.

The earphone is excited, using a frequency generator which can be tuned to vibrate at different sinusoidal frequencies and amplitudes. The static deformation of the membrane is controlled by varying the amplitude of excitation signal using the frequency generator. An 8-bit digital CCD with 2029×2044 square pixels $9\mu m$ in size is used to record the holograms at 30 frames per second. The object is placed 500 mm from the CCD, which satisfies the sampling theorem requirement for efficient use of full sensor area [104]. In-

line time average digital holograms are recorded at different amplitudes of vibration and at frequencies ranging from 1 KHz to 10 KHz. Thus the exposure time is greater than the period of vibration giving rise to a time average recording. Numerical reconstruction is performed using MATLABTM.

Figure 5.4. (a) In-line digital holographic set-up for vibration measurement,

(b) Schematic of the vibrating membrane

For time average recording, the amplitude is modulated by the J_0 function and the phase represents information about the mean static state of the object. If there is any change in the mean static state of the vibrating object at different amplitudes then as discussed previously, the subtracted wavefields (or intensity) of two time average holograms would show the mixing of time average and static deformation fringes (Equations (5.19) and (5.20)). Double exposure holograms of the membrane are recorded at the same frequency but different amplitudes. The subtraction of the reconstructed wavefields corresponding to the resonant frequencies 2.0 KHz, 5.25 KHz, 6.0 KHz, and 7.75 KHz are shown in Figure 5.5.

Two sets of fringes corresponding to Bessel fringes and the mean deformation fringes are clearly observed in Figure 5.5. The deformation fringes extend to the area where the diaphragm is bonded to the frame indicating the bonding characteristics. The fringes in the clamped region attribute to improper bonding of the diaphragm which may create the asymmetric mean deformations while applying vibrations. Furthermore, while the fringe pattern appears to allude that the two sets of fringes are simply superposed, it is seen from Equation 5.19 that this is not so. Indeed, if the two patterns were simply superposed, they could be readily separated by considering the amplitude and phase of the wavefield subtraction.

Figure 5.5. Subtracted wavefields of membrane vibrating at same frequency but different amplitude showing the mixing of vibration and mean static deformation fringes.

Vibration frequencies at (a) 2.0 KHz, (b) 5.25 KHz, (c) 6.0 KHz, and (d) 7.75 KHz.

To separate the Bessel fringes from the mean deformation fringes, it is thus necessary to first determine the amplitude and phase of the two time-average digital holograms and then subtract them as given in Equation (5.21). The mode patterns of the vibrating membrane corresponding to the same frequencies as discussed above are shown in Figure 5.6. These patterns are obtained by subtraction of reconstructed intensities (Equation (5.21 (a))) from two time-average holograms recorded at same vibration frequencies but with slightly different amplitudes. Similar patterns can also be obtained by displaying the

intensity of a single time-average hologram. These patterns are similar to those observed in conventional time average holographic interferometry. For a single time-average hologram, the overlapping zero-order wave and twin image effect needs to be eliminated by pre-processing the hologram. For the two exposure subtraction process, no such pre – processing is required.

Figure 5.6. Vibration mode pattern at frequencies (a) 2.0 KHz, (b) 5.25 KHz, (c) 6.0 KHz, and (d) 7.75 KHz

The mean static state of the membrane under vibration changes the phase of the wavefield. Hence to display only the difference in mean static state between two wavefields, the phase is extracted from each wavefield and then subtracted as per

Equation (5.22). Figures 5.7(a) – (d) shows the resulting phase difference representing only the difference in mean static state for the membrane vibrating at different frequencies. The difference in amplitudes between the two subtracted images for the four different frequencies is similar and hence the difference in mean static state fringes is identical.

Figure 5.7. Subtraction of phase gives the fringe pattern corresponding to mean static deformation during change in vibration amplitudes

Closer inspection of the fringe pattern indicates what appear to be additional phase effects due to the fact that the membrane is vibrating at resonance. These additional phase changes mask the mean deformation fringes in these regions. Also, the amplitudes at

resonant frequencies are much higher than for static deformation if the plate was not vibrating, as is to be expected. This is clear from Figure 5.8 which shows the same membrane only subject to static deformation at zero vibration frequency. Only the fringes due to difference in static states are clearly seen. Indeed even if the plate were vibrating, as long as the amplitude of vibration is small, only fringes due to difference in static state are observed. It is also noted that in this case (Figure 5.7), the difference in amplitude between the two exposures is two and three times larger than the amplitude difference for Figure 5.6.

Figure 5.8. Mean static deformations at two different amplitudes of stationary plate

5.2.3 Amplitude and phase analysis of time-averaged holograms

As indicated in Equation (5.14), the numerically reconstructed amplitude of real image wave is modulated by the zero-order Bessel function which provides the information on the mode shape and amplitudes of vibration of the object. For double exposure method the vibration information of the object is obtained by subtracting the amplitudes in states 1 and 2, similar to electronic speckle pattern interferometry (ESPI) [137].

The numerically reconstructed phase information from time average holograms (Equation (5.17 (b))) is a combination of phase due to object surface roughness information ϕ_o , and the time average phase ϕ_j . ϕ_o varies from $-\pi$ to $+\pi$, whereas ϕ_j is the binary phase (with values 0 and $\pm\pi$) that changes at the zeros of the Bessel function [103]. In the reconstruction of a single time average hologram of object with rough surface, ϕ_o is the source of speckle noise, but by using the double exposure method speckle correlation fringes, representing the difference in mean static deformation in between the two exposures, are seen as modulo 2π fringes. However, in the presence of both static deformation and vibrations, the phase subtraction of time averaged hologram represents the mixing of the mean deformation and the time averaged fringes. A cluster of these phase informations is occurred, which facilitate the precise study of the object vibrations in the presence of mean static deformation. Obviously the behavior of mean static deformation fringes is not the same in vibrating and non-vibrating regions of the object. The presence of mean deformation is thought to create an imbalance which manifests itself in mean static deformation fringes. Thus the behavior of the mean static deformation fringes in the vibrating and non-vibrating regions of the object is useful to study the balancing situation of the object as shown in Figures 5.2 (b) and (c).

5.3 System analysis for lensless magnification

In order to study smaller size objects, there is a need to magnify the object. For lensless system, the magnification is done using a diverging object wave. Increase in the object to CCD distance results as the increase in the magnification of the system. There is a need to analyze the effects of the magnification, on the reconstructed amplitude and phase

information from time average holograms. In this section, the sensitivities of the amplitude and phase fringes are studied with the magnification of the system.

5.3.1 Effect on the sensitivities of vibration amplitude and mean deformation interference phase with magnification

The sensitivity of the amplitude information representing the vibration modes is studied as a function of recording distance. At the same time the effect on phase information, which represents the mean static deformation of vibrating object is also presented.

The reconstructed wavefield from time average hologram at plane (x', y') placed at a distance d' from the hologram plane is obtained by either the Fourier transform method or the convolution method. The convolution method is preferred for shorter recording distances and the image size is independent of reconstruction distance. When the reconstruction distance becomes equal to recording distance, the reconstructed real image wave from the time average hologram remains fundamentally the same as the recorded object wave except for the magnification term i.e.,

$$U(x', y') = O_0(x', y') \exp[i\phi_0(x', y')] J_0[\vec{K} \cdot \vec{z}(x', y')] \quad (5.23)$$

The numerically reconstructed amplitude and phase can be separately calculated from the real image wave as,

$$|U(x', y')| = |O_0(x', y')| \cdot |J_0[\vec{K} \cdot \vec{z}(x', y')]| + \text{Background noise} \quad (5.24a)$$

$$\phi_0(x', y') = \tan^{-1} \frac{\text{Im}(U(x', y'))}{\text{Re}(U(x', y'))} \quad (5.25b)$$

Now, consider two time average holograms recorded at the same vibration frequency but with different amplitudes of vibration. As discussed previously, subtraction of the individually reconstructed amplitudes provides J_0 type fringes with different visibility. However, in this case the subtraction of phases gives the difference in mean deformation of the object.

An in-line digital hologram is recorded by the CCD sensors placed at the plane (ξ, η) as shown in Figure 5.9 (a). For good quality amplitude reconstruction, the sampling theorem should be fulfilled across the entire CCD sensor area. This means that the interference fringe spacing must be larger than two pixels of the CCD sensor. The recording distance requirement basically depends on the object size, wavelength, CCD pixel size, and nature of the reference wave. The condition of digital sampling requires a minimum recording distance between object and CCD ($d_{\min}$), and the better sampling is achieved at all the distances larger than $d_{\min}$.

Figure 5.9. (a) In-line digital holographic recording mechanism, (b) Object illumination by the diverging beam

Illumination by a diverging beam will magnify the amplitude of the object wave by a factor of $(d+l)/l$, where l is the distance of object from diverging source as shown in Figure 5.9 (b). At the same time, the objective speckles size at the hologram plane at a distance d due to an object size S_o is $\lambda d/S_o$. Hence, the smaller the object-to-CCD distance, the smaller the speckle size and larger the phase sensitivity. This means the samplings of digital holograms and of the individual speckles are independent phenomenon. There appears to be two different ways to control the amplitude and phase parts. Following convention, an increase in the recording distance increases the sampling of the interference pattern between the reference and object wave, resulting in increased sensitivity to the amplitude information. On the other hand, double-exposure fringes are controlled by the speckle size, which increases with the recording distance and thus reduces sensitivity to mean deformation fringes.

- Experimental Analysis

The experimental set-up for in-line digital holographic interferometry is shown in Figure 5.10. A thin aluminum membrane 5 mm in diameter is excited sinusoidally at different frequencies and amplitudes by an earphone connected to a frequency generator. Light from a frequency doubled Nd-YAG laser operating at wavelength $0.532\mu m$ is coupled into a single mode fiber coupler which is further split equally into two beams. One of the diverging beams illuminates the vibrating object while the other is collimated to form the in-line reference beam. An 8-bit digital CCD sensor with 2029×2044 square pixels $9\mu m$ in size is used to record the time average holograms at 30 frames per second. The

numerical reconstruction process is performed by using fast Fourier Transform (FFT) algorithm [Equation (2.11)], which is simulated in MATLABTM.

Figure 5.10. Experimental set-up for diverging object wave in-line digital holographic interferometry

The minimum object distance from the CCD to satisfy the sampling theorem requirement is 388 mm. In this experiment, three distances 270 mm, 350 mm and 410 mm are selected and both the vibration (J_0) and mean deformation fringes analyzed at these distances. As discussed previously the vibration mode shape and its amplitude information can be reconstructed from the amplitude part of the reconstructed real image wave, while the reconstructed phase information gives the mean static deformation of the object during vibrations.

The amplitude reconstructed from the holograms at the three distances at a frequency of 2.6 KHz and excitation voltage of 9.5 volts are shown in Figures 5.11(a), (b) and (c). The

reconstructed amplitude fringes show the vibration mode of the membrane. It can be clearly seen that, the sensitivity of the vibration fringes increases as the distance increases.

Figure 5.11. Reconstructed Intensity from time average holograms at (a) 270mm, (b) 350mm and (c) 410mm

A mean static deformation in the vibrating membrane can be introduced by an offset voltage or can occur naturally due the nonlinear mechanical effects. These deformation fringes can be analyzed using the reconstructed phase information. The subtraction of reconstructed phases during double exposure represents only the mean static deformation fringes at relatively lower amplitudes of vibrations and as vibration amplitude increases it mixes with the mean off-set deformation caused by vibrations. Figures 5.12(a-c) shows the subtraction of reconstructed phases from two time average holograms recorded at the frequency 2.6 kHz and at different amplitudes of vibration (excitation voltages are 5 and 8.5 volts) corresponding to the three distances respectively. The mean deformation fringes can be clearly observed at the minimum recording distance of 270 mm, but as the distance increases the fringes are not seen. The effect of zero-crossing phase, which was used for the determination of dark fringes for pure sinusoidal excitation, also appears in

the phase subtracted image, especially at larger reconstruction distances, where sensitivity to amplitude effects are higher.

Figure 5.12. Phase subtraction shown the deformation fringes reconstructed at (a) 270mm, (b) 350mm and (c) 410mm

Thus the effects on reconstructed amplitude and phase information of the vibrating object for different recording distances behave differently, when the object wave is illuminated with a diverging beam. There appear to be two different phenomena that seem to control the amplitude and phase parts. Following convention, an increase in the recording distance, increases the sampling of the interference pattern between the reference and object wave resulting in increases sensitivity to the amplitude modulated time average fringes. On the other hand, double exposure fringes are controlled by the speckle size which increases with the recording distance and thus reduces sensitivity to mean deformation fringes.

Since at the larger distances the sensitivity of amplitude information increases, this simultaneously increases the sensitivity of zero crossing phase information. Thus for larger recording distances, the effect of time average phase can be observed with mean deformation fringes.

5.4 Chapter summary

In this chapter the methodology of time averaged in-line digital holography is explored for vibration analysis. A double exposure method is developed for simultaneous determination of vibration mode shape and mean-static state deformation during vibration cycle. This method is suitable for simultaneous suppression of background noise, caused by in-line geometry, without any pre-processing of holograms. Method for separation of the mixing of time averaged and means deformation fringes is explained. For amplitude subtraction, enhanced and multiplied Bessel fringes are observed while the phase subtraction gives the mean deformation fringes.

A lensless in-line digital holographic microscopy interferometry is presented for vibration analysis of smaller objects. The effects on reconstructed amplitude and phase information of the vibrating objects are studied for the variation in the recording distances. The sampling of digital holograms and of the individual speckles is independently studied and their effects during reconstruction process are presented. The opposite behavior of the sensitivity of reconstructed vibration and mean deformation fringes are presented with the change in the recording distance. In practical situation, the selection of recording distance depends on the preference of the type of deformation measurement requirement. In case of requirement of both the deformations, the optimal recorded distance need to be selected to make sure the proper sampling of speckles and hologram interference pattern. The analysis of the lensless in-line digital holographic microscopic geometry is useful for the vibration analysis of smaller objects and can be readily extended for smaller objects like MEMS diaphragms.

CHAPTER 6

DYNAMIC CHARACTERIZATION OF MEMS DEVICES

New challenges for the dynamic measurement introduced by miniaturization of the test objects require development of reliable advanced testing methods. Integration of mechanical elements, electronics, sensors and actuators on a common silicon substrate by micromachining technology constitute microelectromechanical systems (MEMS) [138-140]. It has a wide range of application in scientific and engineering fields [141-144]. Characterization of the mechanical properties of MEMS structures at different stages of manufacturing is very significant. The purpose of dynamic MEMS testing is to provide feedback about device behavior, system parameters, and material properties for design and simulation process. Also dynamic testing is needed in final devices to test their performance and characteristics. Dynamic characterization of the mechanical properties of MEMS structures is a challenging task.

The proposed lensless in-line digital holographic reflection microscope system is used as novel instrumentation for the dynamic characterization of MEMS. The system aims to use optical full-field measurement methods together with combined computational and experimental methodologies, to implement comprehensive testability procedures in reliability testing of MEMS. It contributes in understanding of MEMS mechanical and material issues during whole component/system life. So the method proposed here will be based on optical full-field techniques, addressing (i) high sensitivity; (ii) non-contact

measurement; (iii) automatic analysis of results; and (iv) reconstruction of exact deformation shape of MEMS structures.

6.1 MEMS diaphragm vibration analysis

6.1.1 The MEMS diaphragm

Vibration analysis of an ellipse shaped MEMS diaphragm with the major and minor axes 7 mm and 6.2 mm respectively is studied. The diaphragm was fabricated by bonding a piezoelectric plate onto a SOI (silicon on insulator) wafer with 20 μm thick device layer. The thickness of the piezoelectric layer was thinned down to about 40 μm by using chemical/mechanical polish. The back side silicon was etched away by deep reactive ion etching. The diaphragm is excited by applying an AC driving voltage across the piezoelectric layer. The photograph of the MEMS diaphragm is shown is Figure 6.1.

Figure 6.1. MEMS diaphragm

Agilent 4294A precision impedance analyzer (40 Hz – 110 MHz) was used to measure the impedance frequency spectrum of the diaphragm. The frequency spectrum is shown in Figure 6.2. The response of the symmetric modes of the diaphragm shows the change in the impedance value, which represents a phase jump at the resonant frequencies. Thus, the phase jumps in Figure 6.2 show the resonant frequencies at the symmetric modes. However the diaphragm also contains the anti-symmetric modes, but the impedance spectrum does not show the response corresponding to these resonant frequencies.

Figure 6.2. Impedance frequency spectrum of the MEMS diaphragm

6.1.2 Vibration modes analysis using in-line digital holography

The experimental set-up used to investigate the vibration analysis of the diaphragm is shown in Figure 6.3. The output from a frequency doubled Nd-YAG laser ($0.532\mu\text{m}$) is coupled into a bifurcated single mode fiber. One fiber arm is used to illuminate the object with diverging beam and the scattered beam from the vibrating object, called object beam

interferes with the collimated reference beam from the second fiber. The intensity of reference beam is controlled to be similar to the object beam, by using a variable attenuator. The polarization of both the object and reference waves are maintained to get the best contrast of the interference fringes. The interference of object and reference beams are recorded on the CCD at a frame rate of 30 frames/sec. The CCD contains 2048x2024 square pixels of $9\ \mu\text{m}$ in size.

Figure 6.3. Experimental set-up for MEMS diaphragm vibration measurements

The mode shapes of the vibrating MEMS diaphragm are obtained from the reconstruction of time-averaged in-line holograms recorded corresponding to the resonant frequencies. The amplitude of the reconstructed real image wave, which is modulated by the J_0 function, gives the mode pattern. Figure 6.4 shows the vibration modes of the diaphragm corresponding to the resonant frequencies as shown in the frequency spectrum shown in Figure 6.2. These pattern can be obtained either by reconstruction of single time

average hologram, or by subtraction of holograms in two states at the same frequency (Equation (5.21)). The effect of zero-order term can be suppressed either by high pass filtering of the hologram before reconstruction or by using the double exposure method discussed before. The reconstructed mode pattern shows good fringe contrast, comparable to images using off-axis geometry for bigger size objects [103]. The use of diverging beam here provides the two advantages - firstly it magnifies the object wave which helps in effective utilization of the entire CCD area, and secondly this kind of geometry is useful to reduce the effect of twin image during reconstruction which creates

Figure 6.4. Vibration modes shapes of MEMS diaphragm verifying the frequency spectrum corresponding to the frequencies (a) 12KHz, (b) 48KHz, (c) 60KHz, (d) 120KHz, (e) 130KHz, and (f) 143KHz

background noise in real image for in-line digital holography. The advantage of digital holography compare to impedance analyzer is to provide the additional full-field vibration mode shape at the resonant frequencies.

Time averaged holograms were recorded corresponding to a wide range of applied frequencies. In addition to the frequencies shown in Figure 6.4, some additional resonant frequencies are also obtained. The mode shapes corresponding to these resonant frequencies are shown in Figures 6.5 (a)-(h). The vibration modes shown in Figure 6.5 can be identified as, (a) (0,1) at 14 kHz; (b) (1,1) at 29 kHz; (c) (2,1) at 45 kHz ; (d) (3,1) at 70 kHz; (e) (4,1) at 90 kHz, (f) (1,2) at 105 kHz, (g) (6,1) at 145 kHz, and (h) (0,4) at 175 kHz, where the numbers in the parentheses refer to the torsional and bending modes. Some of anti-symmetric modes can be clearly seen in Figures 6.5(b), (c) and (e).

Figure 6.5. Vibration modes shapes corresponding to the resonant frequencies (a) 14KHz, (b) 29KHz, (c) 45KHz, (d) 70KHz, (e) 90KHz, (f) 105KHz, (g) 145KHz, and (h) 175KHz

- Vibration amplitude measurements

The amplitude of vibration can be determined from the obtained mode patterns. The Equations (5.14) and (5.3) is used for vibration amplitude measurements. The geometrical factor g' need to be calculated according to the system geometry. The factor $\vec{K} \cdot \vec{z}_v(x', y') = Kz_v g'$, where $K = 2\pi / \lambda$. For the experiment system $\lambda = 0.532 \mu m$ and geometric factor $g' = 1.36$. This factor represents the zeros of zero-order Bessel function (appendix C) of the reconstructed image. The zeros of first order Bessel function used corresponding to the dark fringes for calculating the amplitude values. The time averaged fringes of the diaphragm by increasing the amplitude values at the resonant frequency 15KHz is shown in Figure 6.6. The vibration amplitude values are plotted for different applied voltages and shown in Figure 6.7.

Figure 6.6. Vibration fringes of MEMS diaphragm as a function of applied voltages (a) 0 V, (b) 1.0 V, (c) 1.5 V, (d) 2.0 V, (e) 2.5 V, (f) 3.0 V, (g) 3.5 V, and (h) 4.0 V

Figure 6.7. Vibration amplitude variation with applied voltage for MEMS diaphragm

The vibration amplitude of the diaphragm is measured by the Laser Doppler vibrometer (LDV) system [Polytech OFV-056C]. The amplitude of vibrations is measured at the centre point of the diaphragm. The amplitude values on a few resonant frequencies are compared given Table 6.1.

Table 6.1. Comparison of vibration amplitude measurements

Frequency (KHz)	Vibration Amplitude μm	
	LDV	DH
14	2.4386	2.275
32	0.5356	0.539
40	1.4400	1.321
44	1.2496	1.126

6.1.2 Mean deformation analysis in the presence of vibrations

The main advantage in using digital holography is to obtain the quantitative phase information of the reconstructed image wave. As discussed previously, the numerical reconstructed phase from time-averaged holograms contains two parts, the first part represents object surface roughness and the second part is called time average phase which shows the zeros of the J_0 function. For reconstruction of single exposure hologram, the first part of the phase term reconstructs the object surface roughness information. Thus for object with optically rough surfaces, it contributes to the speckle noise. However double exposure case, if there be any mean static deformation during vibration amplitude change, the subtraction of the phase term represents the mean deformation. Again for rough object surface the mean deformation fringes occurs due to speckle correlation, and for time averaged case the mean static fringes mix with the vibration fringes. For pure sinusoidal vibration of the object, the subtraction of phases of time average and reference hologram provides only the time average phase. This is shown in Figures 6.8(a)-(c) corresponding to the frequencies (a) 14KHz, (b) 45KHz, and (c) 105KHz. Compared to Figure 6.5, all zeros of the J_0 function can be clearly identified from the time average phase. The eventual use of binary jumps is particularly useful in case of higher vibration amplitudes. It is because the time averaged amplitude fringes are modulated by zero-order Bessel function, so for higher order fringes the contrast becomes significantly poor, while the time average phase shows the binary jumps and thus has the same contrast for all orders.

Figure 6.8. Time average phase representing the binary jumps corresponding to the zero of the Bessel function

Figure 6.9. Modulo 2π interference phase representing mean static deformation obtained by applying offset voltage at non resonant frequencies

Although the time average phase contains binary values (with numerical values 0 and $\pm \pi$), it provides a clear representation of the zeros of J_0 function; while the simultaneous presence of static phase appears as the speckle noise. The double exposure method cannot completely remove this noise because of the stochastic variations of speckles in the two exposures. This effect can be seen in Figure 6.5. In order to explore the mixing of the phase information during phase subtraction, first we have considered

the case of pure static deformation which is achieved by selecting a non-resonant frequency and applying an off-set voltage to the membrane between exposures. The phase subtraction represents modulo 2π interference phase same as in conventional digital holographic interferometry. Figure 6.9 shows the pure mean static deformation fringes obtained from time averaged in-line holograms. The holograms are recorded at a non resonant frequency of 25 KHz, at different voltage with increasing offset voltages (0.5 volt, 1.5 volts and 4.5 volts) applied by the frequency generator.

Mixing of the phase fringes is best visualized when the applied offset voltage excites the membrane in resonance. The mixing shows the cluster of mean deformation and time average phases, which represents the exact vibration behavior of the membrane in the presence of mean static deformations. Thus the importance of mean static deformation is to study the actual behaviour of vibrating objects in the presence of mean static change. Figures 6.10(a)-(c) show the patterns corresponding to the different mean and vibration amplitudes at a resonant frequency of 15 KHz. For double exposure recording, the reference hologram is recorded without vibration, and the time-averaged holograms recorded with driving voltages of 1.0, 1.5, and 2.0 volts and corresponding offset voltages 0.75, 1.5, and 2.5 volts respectively. It can be clearly seen in Figure 6.10(a) that the mean deformation fringe also appears inside the time average phase with a phase jump. This phase jump may be attributed to the balancing condition of the membrane created by the offset voltage. As the offset voltage increases, the number of fringes inside the time average fringe also increases (Figures 6.10(b) and (c)).

Figure 6.10. Mixing of mean deformation and time average phases, representing the balancing of the diaphragm in the presence of both vibration and mean deformation

6.2 Vibration characterization of MEMS cantilevers

6.2.1 Cantilevers fabrication and measurements requirements

Aluminium nitride (AlN) films have piezoelectric properties, and represent an alternative to PZT films. Vibration analysis of the AlN cantilevers is performed using the lensless in-line digital holographic method

- Fabrication Details

Fabrication of cantilevers (Figure 6.11) is elaborated in the following 8 steps:

Step 1: Si wafers of orientation and thickness of $\langle 100 \rangle$ and $380 \mu\text{m}$ respectively, was used for the fabrication of cantilevers.

Step 2: This steps shows the formation of Si membrane. Anisotropic etching using KOH was done on the back side of the Si wafer, till a thickness of $15\mu m$ was achieved.

Step 3: The deposition of first layer of Cr Ni is shown in this step. $Cr_{50\%}Ni_{50\%}$ alloy was been sputtered on a heated substrate ($200^{\circ}C$) at 230 watt (0.5 A) using a 7 mTorr Ar gas. A CrNi layer of thickness 150 nm was sputtered and patterned.

Step 4: AlN layer has been deposited in this step. A pulsed reactive DC sputtering machine on a non heated substrate with an input power of 650 watt, an Ar / N_2 gas ratio of 0.65 sccm / 6 sccm and a pressure of 4.9 mTorr, was used for the deposition. Two thicknesses of $1\mu m$ and $1.4\mu m$ were used.

Step 5: The deposition and patterning of the second layer of Cr Ni is shown in this step. Conditions similar to step 3 were used. The thickness of layer deposited was 350 nm.

Step 6: The top CrNi patterned layer was used as a hard mask for AlN etching, as shown in this step.

Step7: This step shows the deposition and patterning of 500 nm thick aluminum pads that were used for wire bonding.

Step 8: The last RIE step removed the silicon which was not protected by the CrNi hard mask, transforming the initial Si membranes into an array of free standing cantilevers.

Figure 6.11. Fabrication steps of cantilevers

The chip of the MEMS cantilevers device is attached to a standard SD card holder as shown in Figure 6.12, which is attached to the frequency generator.

Figure 6.12. Layout of the $300 \times 50 \mu\text{m}$ long cantilevers. The actuation of the cantilevers is done by applying a voltage between the upper and bottom metal electrodes [145].

6.2.2 Imaging and vibration analysis using the LDHM system

- Optical system

A patent pending lensless in-line digital holographic microscopy is explored for imaging and dynamic characterization of MEMS cantilevers. The optical system explained in section 3.2.2.1 is used here. The photograph of the experimental set-up is shown in Figure 6.13. A single mode fiber (core diameter is $10 \mu\text{m}$) is attached to the He-Ne laser. The diverging beam emerging from the output end of the fiber is split into two parts using the beam splitter placed near to the fiber end. One part of the diverging beam illuminates the sample and other incident on the mirror. The beam reflected from the sample (object beam) interferes with the reference beam reflected from the mirror, and form the hologram. The hologram is recorded using the CCD, having 960×1280 pixels with $4.65 \mu\text{m} \times 4.65 \mu\text{m}$ in size. The distance between the sample and CCD adjust the

magnification of the system. The magnification of the system is limited because the pinhole (fiber end) and object distance is restricted by the beam splitter.

Figure 6.13. Photograph of the Experimental set-up of reflection LDHM system

- Imaging and vibrations analysis

The optical microscopic image of the 4 cantilevers electronically connected together are shown in Figure 6.14 (a), and numerically reconstructed image using digital holographic system is shown in Figure 6.14 (b).

Figure 6.14. (a) Optical microscopic image of the cantilevers with 5X magnification, (b) Numerically reconstructed image using the LDHM set-up

- Full field vibration analysis

The behavior of the cantilevers vibrating at the first frequencies is shown in Figure 6.15. Five cantilevers (connected to the one electrode as shown in Figure 6.12) are studied simultaneously. The applied excitation voltage is 0.5 Volt. It is found that all the cantilevers are not vibrating at the same resonant frequency. The scanning the frequencies at the first resonant frequency are performed from 66.85 KHz to 74.40 KHz, with the difference of 0.05 KHz and the vibration behavior of the cantilevers are shown.

Figure 6.15. Vibration behavior of cantilevers at first resonant frequency: (a) 66.85KHz, (b) 66.90KHz, (c) 66.95KHz, (d) 67.0KHz, (e) 67.05KHz, (f) 67.10KHz, (g) 67.15KHz, (h) 67.20KHz, (i) 67.25KHz, (j) 67.30KHz, (k) 67.35KHz, (l) 67.40KHz

The vibration amplitudes of each cantilever are calculated at each frequency and plotted in Figure 6.16. Vibration amplitude is calculated using Equation (5.14) as explained in section 6.1.2. However since LDHM system has been used for such measurements, so the optical geometry is different because of normal illumination and observation angles and $\lambda = 0.633\mu m$. It can be clearly observed that, the resonant frequencies of the cantilevers

change from right to left side. This means in terms of fabrication process these are the cantilever from centre to edge side of the wafer.

Figure 6.16. Change in vibration amplitudes of cantilevers for first resonant frequencies

Figure 6.17. Vibration behavior of cantilevers at second resonant frequency: (a) 411KHz, (b) 412KHz, (c) 413KHz, (d) 414KHz, (e) 415KHz, (f) 416KHz, (g) 417KHz, (h) 418KHz, (i) 419KHz, (j) 420KHz, (k) 421KHz, (l) 422KHz

There may be many possible reasons for shift in the resonance frequencies of cantilevers such as difference in stiffness coefficient [146], non-uniform fabrication process, or cantilevers dimension effects etc. Similar effect is also observed for the second resonant frequency, and shown in Figure 6.17. Here the frequencies are tune from 411 KHz to 422 KHz with the interval of 1 KHz.

6.3 Dynamic thermal deformation analysis of MEMS micro-heater:

The capabilities of LDHM reflection system is demonstrated for dynamic thermal characterization of MEMS micro-heater.

6.3.1 MEMS micro-heater

The chip out lay of the MEMS micro heater is shown in Figure 6.18 (a). Here an array of micro heaters are fabricated, the single typical micro-heater is shown in Figure 6.18 (b). Here the thermal deformation in the electrodes (shown in blue color) appears because of the applied voltages between the electrodes.

Figure 6.18. (a) Out lay of MEMS micro-heater chip, and (b) single micro-heater sample

6.3.2 Thermal measurements

- Experiment

The experimental set-up shown in Figure 6.13 is used for thermal deformation study of the micro-heater. The electrodes were connected to the power supply. A series of holograms were recorded corresponding to the different voltages between the electrodes.

The optical microscopic image of the single micro-heater sample is shown in Figure 6.19 (a). The hologram of the same sample is recorded and the numerically reconstructed amplitude image of the hologram is shown in Figure 6.19 (b). Two points on different electrodes of micro heater as shown in Figure 6.19 (a) are used to calculate the thermal deformation value at different voltages.

Figure 6.19. (a) Optical Microscopic image of MEMS micro-heater at 5X magnification, (b) Digital holographic numerically reconstructed image

- Thermal deformation measurements

For thermal deformation measurements, the numerical reconstruction of the hologram is performed. The holograms were recorded by varying voltages from 1 volt to 10 volts. The phase information is reconstructed corresponding to the each state. The subtraction of the phases of the deformed state (corresponding to the applied voltage) and reference state (without applying voltage) provides the deformation fringes. Figures 6.20 (a)-(l), shows the deformation fringes for the voltage changes from 1.0 volts to 3.7 volts. Deformation fringes can be clearly observed in the electrodes. As expected the number of fringes increases with increase in the voltage which shown the increase in the thermal deformation with applied voltages.

Figure 6.20. (a) Thermal deformation profile in MEMS micro-heater at applied voltages (a) 1.0V, (b) 1.25V, (c) 1.5V, (d) 1.75V, (e) 2.0V, (f) 2.25V, (g) 2.5V, (h) 2.75V, (i) 3.0V, (j) 3.25V, (k) 3.5V, and (l) 3.75V

The deformation fringes corresponding to the higher voltages are shown in Figures 6.21 (a)-(l), corresponding to the voltages varying from 7.0 volts to 9.7 volts. The number of fringes in the electrode is large which shows the higher thermal deformation. It can be also observed that, the deformation fringes are also expended in the other electrodes and increases with increase in temperature. It shows the full field thermal deformation in the device at higher voltages. Thus, this kind of analysis is particularly useful for full field study of smaller devices, where different components of the device showing different deformations behavior, subject to the same input conditions.

Figure 6.21. (a) Thermal deformation profile in MEMS micro-heater at applied voltages (a) 7.0V, (b) 7.25V, (c) 7.5V, (d) 7.75V, (e) 8.0V, (f) 8.25V, (g) 8.5V, (h) 8.75V, (i) 9.0V, (j) 9.25V, (k) 9.5V, and (l) 9.75V

Figure 6.22. Thermal deformation measurement at different electrodes of micro-heater

The numerical value of thermal deformation quantity is measured at the two points as shown in Figure 6.19. The deformation values are plotted as a function of applied voltage as shown in Figure 6.22. This kind of analysis is useful to study of different parts of same device simultaneously corresponding for the same input conditions.

Figures 6.20-6.22 shows the phase map for out-of-plane deformations. There is possibility to include methodology for in-plane deformation measurements with the system. This kind of measurement is possible by modifying optical geometry with changing illumination and observation direction. The deformation can be divided into out-of-plane and in-plane deformations components.

6.4 Chapter summary

The vibration characterization MEMS diaphragm is presented using in-line digital holography. The effect of mean static state on the phase in time averaged digital holography is explained. It is proved that the subtraction of phase information of the holograms recorded at the vibration state and reference state show the cluster of the time average and mean deformation fringes. The interference fringes are also obtained within the time average phase with a phase jump. Furthermore the capabilities of the LDHM reflection set-up are explored for MEMS device characterization. The vibration characterization of MEMS cantilevers is presented using time average principle. Thermal deformation of a MEMS micro-heater is analyzed based on the principle of the phase subtraction corresponding to the different thermal deformations. The different behaviors of the different components of the device are presented corresponding to the same input conditions.

CHAPTER 7

CONCLUSIONS AND FUTURE WORKS

In the present research, in-line digital dynamic holography is explored for imaging and measurement applications. The main contents include the development of lensless in-line digital holographic microscopic (LDHM) system, new methodologies are presented for the 3D imaging of micro-particles and their dynamic analysis, time-averaged in-line digital holography is developed for vibration analysis, dynamic characterization of MEMS devices are presented. In this chapter, the main contributions presented in the thesis are summarized. Some future direction of the presented research work is than outlined.

7.1 Contributions

The following are the conclusions of the findings of the research work presented in the thesis.

- The analysis and capabilities of in-line digital holographic system are explored. It is explained by the information recording capability of in-line holograms followed by reconstruction methodologies. The optimization of the recording set-up is presented which is based on the analysis of the digitally sampled hologram information and spatial bandwidth product. The analysis of numerically reconstructed amplitude and phase information is presented for different recording distances and experimentally demonstrated. It is shown that the digital sampling requirement of hologram fringes is

not sufficient to reconstruct the phase with highest sensitivity, while previous works are limited to amplitude information only. It is also explained that the recording of the spatial frequency of objective speckles affects the sensitivity of the reconstructed phase information. At the distance, between object and CCD, less than minimum recording distance requirement, although the sampling requirement is not fulfilled across the full sensing area of the CCD, but better phase sensitivity is achieved because of higher spatial frequencies of speckles. However at larger recording distances even the full sensor area is effectively used but poor phase sensitivity is obtained.

- Lensless in-line digital holographic microscopic (LDHM) system (patent pending) has been proposed as a novel tool for dynamic 3D imaging and micro-measurements applications. The methodology of LDHM system is developed. The study of the parameters of the system is presented and experimentally verified. A new method is developed to retrieve the image magnification in the case of converging reconstruction wave. This is achieved by pixel resizing caused by the use of converging beam for digital hologram reconstruction. The correct pixel size for the magnification can be achieved by appropriately zero padding the digital hologram prior to reconstruction. The proposed method is most useful to significantly improve precise magnification analysis for LDHM. Although it is illustrated that the use of the method only for the case of in-line holographic analysis, this approach can be used to retrieve the magnification in any case where FT reconstruction is used in conjunction with converging reconstruction wave. The geometries for LDHM for transmission

system for 3D imaging application and reflection for dynamic micro-measurements are also studied.

- ❑ In-line DH system is explored for 3D particle visualization and tracking. Methodology for depth and size measurements of particles is presented for collimated and LDHM system. The 3D particles imaging capability using single hologram is compared with conventional microscopic images. A new subtraction method of reconstructed wave fields for particles image slicing in 3D is presented. The effects of zero order term, conjugate image wave and more importantly the particles outside the plane of interest (defocused images) are simultaneously minimized, and thus improve the contrast of reconstructed amplitude images. This method is useful to slice in-line digital holograms to display only in-focus particles at any particular plane. Furthermore all this is accomplished from a single hologram with no additional pre or post processing required. This method is most effective for particle analysis because of the small depth of focus, and hence best for the analysis of very small particles in volume.

A lensless transmission digital holographic microscope is explored for micro-particles analysis. The study of polymer micro-spheres of size $9.6\mu m$ is presented in 3D with a depth resolution of about $50\mu m$. For the study micro-particles imaging, the behavior of depth profile of the particles at different spatial location (axial and non-axial location) is not exactly the same. It is because of the shift of the pixels representing the reconstructed particle image with the reconstruction depth. To control the shifting

the particles pixel position, the zero-padding of the hologram is demonstrated. This can control the shifting effect and thus improve the system accuracy for depth localization of particles located at different spatial locations.

The methods for dynamic analysis of micro-particles in 3D are demonstrated. Two different methodologies are presented for such study. In the first method, the recorded holograms recorded during the motion of particles are added first. The dynamic behavior of particles in 3D is studied during the numerical reconstruction of the final hologram (addition of holograms). The velocities of particles in different depth are also measured. The second method is based on reconstructed intensity threshold. This method is presented as best suitable for the study of larger number of holograms. The steps of algorithm are presented followed by displaying methodology of the dynamic behaviors of micro-particles. The 3D velocity components of 4 particles are presented. This kind of analysis, not possible with any PIV system, is useful for observing the 3D dynamic behaviors of particles and can be used to predict the motion of particles in 3D.

- The theory of In-line time-averaged digital holography for the study of the vibration characteristics has been established. However, the previous work is focused only on time-averaged off-axis geometry. A double exposure method is developed which is suitable for numerical reconstruction of time averaged in-line holograms. It is presented that, using the double-exposure approach, simultaneous determination of vibration mode shape and mean static state deformation during a vibration cycle are

obtained. This approach is also presented as suitable for simultaneous suppression of background noise, caused by in-line geometry, without any preprocessing of holograms. However, the double-exposure method results in the superposition of the Bessel fringes owing to vibration and of the mean deformation fringes owing to double exposure. Separation of these fringes requires that the amplitudes and phases of the individual holograms be determined first and then subtracted. For amplitude subtraction, enhanced and multiplied Bessel fringes are observed, whereas phase subtraction presented the mean deformation fringes. It is also presented that, in addition to mean deformation fringes, the phase difference shows the phase jump that is due to the resonating membrane that masks the fringes in certain regions of the vibrating object.

A lensless in-line digital holographic interferometry is presented to study smaller size objects. The effects on reconstructed amplitude and phase information of the vibrating objects were studied for different recording distances when the object wave was illuminated with a diverging beam. It is shown that, there are two different phenomena that control the amplitude and phase parts. An increase in the recording distance increases the sampling of the interference pattern between the reference and object wave, resulting in increased sensitivity to the amplitude-modulated time-averaged fringes. On the other hand, double-exposure fringes are controlled by the speckle size, which increases with the recording distance and thus reduces sensitivity to mean deformation fringes. The experimental observation and a theoretical explanation for this contradictory phenomenon are presented.

- ❑ Vibration characterization of a MEMS diaphragm is investigated using lensless time-averaged in-line digital holography. The resonant frequencies are identified and vibration amplitudes measured and compared with other existing methods. Some additional vibration modes are presented using LDHM, which were not obtained using other methods. The analysis and capability of the numerically reconstructed amplitude and phase information from in-line time averaged holograms is presented to study the MEMS vibrations. Particularly the effect of mean static state on the phase in time averaged digital holography is explored. It is proven that subtraction of phase information of the holograms recorded at the vibration state and reference state shows that a cluster of the time average and mean deformation fringes which can be used to analyze the vibrations in the presence of mean deformations. The interference fringes are also obtained in time average phase with a phase jump compared to the main deformation fringes.

- ❑ The capabilities of the LDHM reflection set-up are explored for MEMS device characterization. The vibration characterization of MEMS cantilevers is presented using time-average principle. Full field vibration analysis of micro-cantilevers ($50\mu m \times 300\mu m$) is presented. Systemic shifts in the resonant frequencies ($\sim 5\%$) of similar cantilevers are presented. Thermal deformation of a MEMS micro-heater is analyzed based on the principle of the phase subtraction corresponding to the different thermal deformations. The different behaviors of the different elements of the device are presented corresponding to the same input conditions.

7.2 Future directions

In this thesis, methodology and experimental investigations of the in-line digital holography is performed for transmission and reflection based systems. Based on the presented studies, the directions for future development are suggested as follows:

- ❑ The development of the methodology for in-line based digital holographic systems is the primary concern of this project. For transmission 3D microscopic imaging applications, particles imaging and dynamic analysis have been performed. Due to poor resolution of available CCD, the system is restricted to reconstruct the images in planes parallel to the CCD plane. It limits the application of the system to visualize the micro-objects from single direction only. Thus for the objects located along the line which is parallel to the optical axis, the system is either not able to identify them, or not able to identify the object size in z-dimension, and the further improvement of the system is required. One suggestion is to view the objects from two perpendicular directions. The development for the methodology is recommended for simultaneous analyse the different views, and merge them together to provide the best exploration of capability of the system for 3D dynamic micro-analysis.

- ❑ It is presented that for both transmission and reflection LDHM systems, the imaging of the object is performed using the amplitude information of the reconstructed wavefield. However, it is also presented the use of the reconstructed phase information for the double exposure method. The phase reconstruction from single in-line hologram is noisy because of the presence of in-line zero-order term and twin

image wave. The methods for analysis of the pure phase information from in-line holograms need to be explored for full utilization the capabilities of the system.

- ❑ The methodology of time averaged in-line digital holography is performed for vibration analysis. The analysis of sensitivity of phase information is presented as a function of recording distance. This kind of analysis is particularly significant when using LDHM for dynamic characterization of micro-size objects. The capabilities of the LDHM system are presented for dynamic studies of MEMS devices by using time averaged and interferometric methods. Further optimization of the LDHM system depending on the measurement requirements is recommended, the requirement is to study the system accuracy and capability which help to develop a very simple, robust, and noble tool for dynamic micro-metrology.

- ❑ A novel LDHM reflection system has been developed using a very simple and compact optical set-up. The novelty of the system is the compact optical geometry with minimum number of optical components (only a beam splitter and mirror), and the developed numerical algorithm for characterization that is only suitable for the investigating system. Indeed for commercial exploitation the design does not need the additional mirror, because the corresponding face of the beam splitter could be suitably coated for this purpose. The design of smaller size beam splitter and coupling of fiber to beam splitter need to be explore for development of robust commercial system.

LIST OF RELEVANT PUBLICATIONS

Research papers in international journals

1. V. R. Singh, A. Asundi, J. Miao, Z. Wang, and G. Hegde, "Dynamic Characterization of MEMS diaphragm using time averaged in-line digital holography", *Optics Communications*, Vol. 280, Issue 2, pp. 285, 2007.
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1. V. R. Singh, A. Andrei, C. Gorecki, L. Nieradko, and A. Asundi, "Characterization of MEMS cantilevers using lensless digital holographic microscope", Proc. of SPIE, Vol. 6995, pp. 69950F-1-8, 2008.
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US Patent Pending

“A HOLOGRAPHIC MICROSCOPE and a METHOD of HOLOGRAPHIC MICROSCOPY”, application under process since September 2007.

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APPENDIX A

SPECIFICATION OF THE MAJOR COMPONENTS USED DURING EXPERIMENTATION

1. Laser Sources

(i) Coherent VerdiTM laser [147] is used in vibration measurement of aluminum membrane and MEMS diaphragm. Specification:

Type: Solid State, diode-pumped, frequency-doubled Nd-YVO₄.

Laser output: CW, green at $0.532\mu m$

Power: Adjustable from 30mW to 2W.

Features: Long coherence length, long term out-put stability, adjustable output power.

(ii) Laser system used for reflection LDHM system:

Type: HeNe Laser

Laser output: CW, Red at $0.6328\mu m$

Power: 5 mW

(iii) Laser system from Power Technology Incorporated used for transmission LDHM system,

Type: Diode laser

Laser output: CW Blue at $0.405\mu m$

Power: 25 mW

2. CCD Cameras

(i) KODAK Mega plus CCD camera (Model 4.1i) used for vibration measurement of aluminum membrane and MEMS diaphragm. Specifications:

Array size: 2029X2044

Pixel size: 9.0X9.0 μm (square format)

Dynamic Range: 8 or 10 bit

Frame Grabber: UltraII PCI [148], capture at the rate of 30 frame/sec

(ii) Imaging Source FireWire Monochrome CCD camera [149] used in transmission and reflection LDHM systems. Specification:

Array size: 1280X960

Pixel size: 4.65X4.65 μm (square format)

Dynamic Range: 8 bit

Image capture software: IC Capture [150]

APPENDIX B

SPECIFICATION OF USAF TARGET RESOLUTION

Table B.1 USAF test target resolution chart (group 5, 6 & 7)

Group	Element Number	Lines pairs/mm	Line width (μm)
5	1	32.00	15.625
	2	35.92	13.920
	3	40.32	12.401
	4	45.25	11.050
	5	50.80	9.843
	6	57.02	8.769
6	2	71.8	6.964
	3	80.6	6.203
	4	90.5	5.525
	5	102.0	4.901
	6	114.0	4.386
7	1	128.0	3.906
	2	144.0	3.472
	3	161.0	3.106
	4	181.0	2.762
	5	203.0	2.463
	6	228.0	2.193

APPENDIX C

BESSEL FUNCTION OF THE FIRST KIND

1. Plot of the Bessel function of the first kind $J_n(x)$

Table C.1 Zeros of the Bessel function of first kind $J_n(x)$

s	$n = 0$	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$
1	2.4048	3.832	5.135	6.379	7.586	8.780
2	5.520	7.016	8.147	9.760	11.064	12.339
3	8.654	10.173	11.620	13.017	14.373	15.700
4	11.792	13.323	14.796	16.224	17.616	18.982
5	14.931	16.470	17.960	19.410	20.827	22.220
6	18.071	19.616	21.117	22.583	24.018	25.431
7	21.212	22.760	24.270	25.749	27.200	28.628
8	24.353	25.903	27.421	28.909	30.371	31.813
9	27.494	29.047	30.571	32.050	33.512	34.983