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# Design and evaluation of a fullsensitivity tilt scanning interferometry system for displacement field tomography and profilometry

By

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A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of

Doctor of Philosophy of Loughborough University

November 2012 © Bona Burlison 2012

### Abstract

This thesis reports the investigation and further development of a tilt scanning interferometry system for surface profilometry and sub-surface tomographic applications. A new 3D full sensitivity interferometry system extends the work carried out on a previous prototype that was capable of measuring displacement along one lateral plus the axial component. Depthresolved imaging is achieved by the acquisition of a sequence of 2D interferograms whilst the illumination beam undergoes a constant rate of tilt and full sensitivity displacement is achieved by performing scans from multiple illumination directions. The comparison of phase volumes from two successive series of scans enables 3D displacement fields to be determined.

The working principle that describes the technique is presented, covering the reconstruction of a depth-resolved sample from the detected intensity distribution. The system performance is studied, including measurement repeatability and factors that affect the depth resolution and depth range. Depth resolution is fundamentally limited by the range of the illumination tilting angle and the new system design enables a larger range. However, the resolution is degraded by a frequency chirp that appears in the temporal interference signal when a large tilting range is scanned. It is shown through a numerical simulation that the chirp depends on the curvature of the illumination wavefront and also on the position of the pivot axis of the illumination beam. Data processing methods are proposed to overcome these limitations and their effects are illustrated with experimental measurements of opaque surfaces and a weakly scattering phantom with internal features.

Displacement measurements involving a controlled rigid body rotation and tilt of a weakly scattering phantom were completed to validate the expected deformations. Both in-plane and out-of-plane components were measured.

**Keywords**: Tilt scanning interferometry, profilometry, angular spectrum scanning, optical coherence tomography, depth-resolved metrology, depth-resolved displacements

## Acknowledgements

I would like first to express my gratitude to Dr. Pablo Ruiz, my principal Ph.D. research supervisor, for his guidance throughout this Ph.D. study, as well as his invaluable share of his long research experience in optics, patience and constant enthusiastic research support. Thanks are also for Prof. Jonathan Huntley, my Ph.D. co-supervisor, for his comments and modifications on the submitted journal paper and thesis and for his help throughout the project.

I am also indebted to Dr. Manuel De La Torre-Ibarra, a visiting researcher from Centro de Investigaciones en Optica (CIO) Mexico, who has substantially helped me in learning and building up my knowledge of optics. Without the assistance and guidance from Dr. Gustavo Galizzi, visiting researcher from Instituto de Fisica Rosario, Argentina, this project would not have been possible – his help with complex demodulation, a core part of the data processing in my research. Help and tutorials from both Manuel and Gustavo in Matlab programming for hardware communications are also greatly appreciated.

The experimental activities of this research would never have been realised without the supplies of mechanical components from the workshops, to whom I would like to extend my thanks to: Mr. Dave Britton and all technicians in the Wolfson School's machine workshop for making the required optical components mounts in the setup. My thanks are also due to Mr. Pete Wileman, the health and safety officer of Wolfson School, who always made sure everything happened in a safe environment and for allowing me to work; and also to Mr. Clive Turner, Mr. Andy Price and Mr. Darren Smith for making sure the IT equipment was always in working order. Other help in research background from Mr. Kanik Palodhi, a Ph.D. research cohort, and Prof. Jeremy Coupland from the Optical Engineering group, for the sharing of their knowledge regarding optical aberrations are also greatly acknowledged.

Supports and help from lab mates and office colleagues are also appreciated. In particular the help from Adel E. Elmahdy for ensuring I always had the correct tools available; Tran Nam Nguyen for his help with the organisation of the thesis; and Taufiq Widjanarko for his help with the thesis and keeping me entertained with his sense of humour, being a fan of British TV comedy shows! Also I extend my appreciation to my fellow Ph.D. colleagues Semanti

Chakraborty, Maryam Haghighi Abyaneh, Maria Mirgkizoudi, Shabnam Rashtchi and Tahir Tarvaz for making work always a pleasant place to come to.

Non-academic but moral support to keep me 'fully-charged' for work are also acknowledged: Nikki Hunt and Durga Sivasathiaseelan for their friendship and for being there for me when times were tough; Smeeta Fokeer, my special friend and her guidance with being a postgraduate student. A very special mention must be made to my best friend Devasuda Anblagan for keeping me sane and smiling throughout the entire project and also for always being there for me outside the workplace. Many thanks go to my housemates Borja Garcia and Aniruddha Majumder for putting up with me. Back home indeed my love and thanks always for Mum and Dad for their constant moral and financial support. A special mention goes to Lauren Wiltshire for being like a sister to me, she made going back home something to really look forward to.

This project has been supported through the EPSRC grant to whom I would like to extend my gratitude and appreciation.

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Burlison, B.S.H., P.D. Ruiz, and J.M. Huntley. *High-resolution tilt scanning interferometry* system for full sensitivity depth-resolved displacement measurements in weakly scattering materials. in *Fringe 2009, The 6th International Workshop on Advanced Optical Metrology.* 2009. Nürtingen: Springer-Verlag.

B. S. H. Burlison, P. D. Ruiz, and J. M. Huntley, "Evaluation of the performance of tilt scanning interferometry for tomographic imaging and profilometry," *Optics Communications*, vol. 285, no. 7, pp. 1654–1661, Apr. 2012.

Ruiz, P.D., B.S.H. Burlison, and J.M. Huntley. *A performance study of tilt scanning interferometry in tomographic imaging and profilometry*. in *Photon12*. 2012. Durham University.

## List of abbreviations

1D, 2D, 3D	1-dimensional, 2-dimensional, 3-dimensional
AS	Aperture stop
CBS	Cube beam splitter
CCD	Charge-coupled device. Used in photodetector arrays
CMOS	Complementary metal-oxide semiconductor
СР	Compensating plate
DC	Direct current. Acts as a zero frequency term in the Fourier spectrum
DIC	Digital image correlation
D-OCT	Doppler optical coherence tomography
DSPI	Digital speckle pattern interferometry
FD-OCT	Fourier-domain optical coherence tomography
FEMU	Finite element model updating
FOV	Field of view
FWHM	Full width at half maximum
GUI	Graphical user interface
HSI	Hyperspectral interferometry
HWP	Half-wave plate
LCI	Low coherence interferometry
LS	Light source
MRI	Magnetic resonance imaging

NA	Numerical aperture
OCT	Optical coherence tomography
OF	Optical fibre
PBS	Plate beam splitter
PC	Personal computer
PCBS	Polarising cube beam splitter
PCMRI	Phase contrast magnetic resonance imaging
PC-SOCT	Phase-contrast spectral optical coherence tomography
РН	Pinhole
PSF	Point spread function
PS-OCT	Polarisation-sensitive optical coherence tomography
PZT	Lead zirconate titanate. Used in piezoelectric devices
RG	Ramp generator
RAM	Random access memory
RHS	Right-hand side. Used to describe an equation
RMS	Root mean square. A measure of the magnitude of a signal.
SFC	Spatial frequency comb
SFCF	Spatial frequency comb of fireworks
SLM	Spatial light modulator
SOCT	Spectral optical coherence tomography
SS-OCT	Swept-source optical coherence tomography
SWLI	Scanning white light interferometry
TD-OCT	Time-domain optical coherence tomography

TM	Tilting mirror
TSI	Tilt scanning interferometry
VFM	Virtual fields method
WBS	Wedge beam splitter
WSI	Wavelength-scanning interferometry
WTI	Wavelength-tuning interferometry

## Nomenclature

SI units are indicated here. Throughout the text, however, other units may be specified in the text when it may be more convenient.

α	Illumination beam azimuth (rad)
$eta_{ m m}$	Diffraction angle for the m-th order (rad)
γ	Parameter representing the window function
$\Delta eta$	Maximum change in diffracted angle (rad)
$\Delta  heta_0$	Total tilting range of the illumination beam (rad)
$\Delta \theta_{\rm beam}$	Tilting range of the illumination beam (rad)
$\Delta \theta_{ m mirror}$	Tilting range of the tilting mirror (rad)
$\Delta \phi$	Change in phase (rad)
$\Delta f$	Spectral bandwidth (cycles per scan)
$\Delta f_{ m shift}$	Maximum variation in the time dependent frequency shift throughout a scan (cycles per scan)
$\Delta r$	Displacement vector (m)
$\Delta z$	Sample thickness (m)
$\Delta z_{\rm range}$	Depth range (m)
δz	Depth resolution (m)
$\delta  heta_0$	Incremental tilt angle (rad)
δt	Number of successive frames between tilt increments(frames)
3	Cartesian coordinate along the horizontal axis of the image plane (m)
η	Cartesian coordinate along the vertical axis of the image plane (m)

$ heta_0$	Angle of illumination (rad)
$\dot{ heta}_0$	Angular velocity of the tilting illumination beam (rad per frame)
$\theta_0(t)$	Instantaneous angle of illumination (rad)
$ heta_1$	Refracted angle of propagation (rad)
$ heta_{ m C}$	Central angle of illumination (rad)
λ	Wavelength of the light source (m)
ξ	Refraction parameter
π	3.14159
$\phi$	Phase (rad)
χ	Ratio of the refractive indices of the sample and its surrounding medium
A <sub>o</sub>	Amplitude of the object wave $(\sqrt{W/m^2})$
A <sub>r</sub>	Amplitude of the reference wave $(\sqrt{W/m^2})$
<i>a</i> <sub>1</sub> , <i>a</i> <sub>2</sub> , <i>a</i> <sub>3</sub>	Plane coefficents
а	Quadratic phase coefficient (rad)
С	Camera detector array
С	Cartesian coordinates of the centre of the curvature of the divergent beam
d	Distance from the pivot axis to a point in the object (m)
F	Frequency of the diffraction grating (Grooves per m)
f	Focal length (m)
f	Temporal frequency (cycles per frame)
$f_{\text{carrier}}$	Carrier frequency (cycles per scan)
$f_{ m shift}$	Time dependent frequency shift (cycles per scan)

h	Height vector
Ι	Intensity (grey levels or W/m <sup>2</sup> )
Ĩ	Fourier transform of the intensity signal ( $\sqrt{W/m^2}$ )
$ ilde{I}_{ ext{Rereg}}$	Reregistered Fourier transform of the intensity signal ( $\sqrt{W/m^2}$ )
i	$\sqrt{-1}$
j	Integer index
K	Sensitivity vector
k	Wavenumber (rad m <sup>-1</sup> )
k	Wave vector
$\mathbf{k}_{\mathrm{h}}$	Height component of the sensitivity vector
<b>k</b> <sub>i</sub>	Illumination vector
<b>k</b> <sub>o</sub>	Observation vector
L	Lens
М	Mirror
М	Magnification
т	Horizontal coordinate on the detector (pixels)
$N_f$	Number of frames
$N_s$	Number of samples
п	Vertical pixel coordinate (pixels)
$n_0$	Refractive index of the surrounding medium
$n_1$	Refractive index of the sample
0	Object
OA	Distance from the coordinate system origin to the pivot point (m)

Р	Polariser
$p_x$	Pixel pitch along the x-axis on the photodetector array (m)
p <sub>y</sub>	Pixel pitch along the <i>y</i> -axis on the photodetector array (m)
R	Radius of curvature of the divergent illumination beam (m)
R	Reference beam
t	Time variable during the acquisition sequence (frames)
u	In-plane displacement along <i>x</i> -axis (m)
ν	In-plane displacement component along <i>y</i> -axis (m)
$\widetilde{W}(\widehat{f})$	Window function ( $\sqrt{W/m^2}$ )
w	Out-of-plane displacement component (m)
x	Cartesian coordinate (m)
У	Cartesian coordinate (m)
Ζ	Cartesian coordinate (m)
Z <sub>max</sub>	Maximum penetration depth within the sample (m)

### Introduction and research overview

#### **1.1 Introduction**

Experimental mechanics is currently contemplating tremendous opportunities of further advancements thanks to a combination of powerful computational techniques and also fullfield non-contact methods to measure displacement and strain fields in a wide variety of materials. In some cases, the inherent 3D nature of the problem means that measurement of surface displacement or strain, and simplifying assumptions (either geometric or of uniform and homogeneous material properties) are not sufficient to fully understand the structural behaviour of the physical system under study. Related to this is a research question, among others, that has inspired the work presented in this Thesis: "What is the spatial distribution of mechanical properties in the human cornea?" This is a highly 3D problem, as the cornea is made of collagen layers with a composite like structure, with different thicknesses and mechanical properties. Ablative refractive surgery, aimed to correct corneal refraction by changing the corneal curvature with excimer lasers, leads to a modified corneal structure which, under the permanent load of the intraocular pressure, can lead to long term unwanted effects that usually require further treatment. Current pre-surgery screening (decision to operate or not) is mainly based on corneal thickness rather than material compliance due to both thickness and mechanical properties of the tissue. However, a thick but too compliant cornea may deform beyond the expected profile after operation. It would be therefore important to know the material properties of individual corneas if any sensible predictions on long term effects want to be made. In order to evaluate position dependent properties within the tissue, inverse methods such as Finite Element Updating (FEMU) [1] or the Virtual Fields Method (VFM) could be used [2]–[4] They work at their best when provided with dense and multicomponent experimental displacement (or strain) data, i.e. when all orthogonal components of displacements (or all components of the strain tensor) are known at points closely spaced within the volume of the material under study. They would require measurements of the 3D displacement field inside the tissue due to known loads and with known boundary conditions. As none of these are easy tasks, especially for *in-vivo* studies, this problem remains open and of great interest in corneal biomechanics.

This thesis was approached with a problem like this in mind, with a view in the long term and hoping to contribute with a step in that direction. This work is focused on the development of a non-contact optical technique that could eventually provide the required full 3D displacement fields through the thickness of the corneal tissue.

Optical methods dominate a significant area within the field of metrology. They have the advantage of having the ability to test materials and tissues in a whole-field, non-invasive, non-contact way, thereby the ability to inspect a sample without damaging it. This allows the examination of materials that are difficult to test due to certain properties or its location. Another advantage of non-contact techniques is that the measurement itself does not affect the testing. In a contact method, the sample is loaded when touched, which may affect the reading. Optical methods also have the capability of performing sub-surface imaging, and optical coherence tomography (OCT) is perhaps the most well-known technique in the field at the moment. It relies on the use of multiple wavelengths, usually in the form of broadband or swept (frequency tuned) sources [5]. A drawback with broadband illumination is that it presents problems with sample dispersion and spectral absorption.

This thesis studies and further develops an alternative approach to broadband OCT. Known as tilt scanning interferometry (TSI), it relies on recording a sequence of monochromatic interferograms while tilting the illumination beam. The recorded data is then used to reconstruct the 3D internal microstructure of a semi-transparent scattering sample. A proof-

of-principle TSI system was demonstrated in 2006 and used to reconstruct cross-sections of a sample as well as to measure depth-resolved displacements within it [6]. It was shown that the depth resolution was inversely proportional to the illumination beam tilting range, and a 1.1mm depth resolution was achieved. Using phase information of the optical field, the system was able to measure the depth-resolved spatial distribution of the out-of-plane and one in-plane components of the displacement field.

The work presented in this thesis took that first TSI system as a starting point for the development of a new 3D full-sensitivity system – one that was able to produce depth-resolved reconstructions of semi-transparent samples as well as provide displacements in the out-of-plane and both in-plane lateral directions.

#### 1.2 Goal of the research work

The goal of this research work was to design, build and test a new TSI system to overcome the limitations of the first prototype, with a focus on: 1) improving the depth resolution; 2) adding full sensitivity measurements capability; and 3) undertaking an in-depth study of system performance.

#### **1.3 Organisation of the thesis**

This thesis is organised as follows: Chapter 1 presents a description of the motivations behind the research that was undertaken, highlighting the scope of the project, the goals of the research and their relevance and relation to previous work. Chapter 2 provides a review of the published literature on phase-contrast depth-resolved optical measurement techniques, including a brief description of the technologies and the achievements from other researchers. Chapter 3 details the working principle behind tilt scanning interferometry including the depth resolution and phase equations. This is followed by a description of the first prototype setup. Chapter 4 opens with a description of the attributes and limitations of the prototype system described in Chapter 3, which informed and guided the design of a new full sensitivity system. The chapter goes on to describe the details of the new design, the main instrument subsystems, the graphical user interface used to control the hardware and record images and finally a description of the data processing steps taken to reconstruct the sample inner structure. Chapter 5 presents an investigation into the performance of the new full sensitivity setup including the repeatability of the system during multiple acquisitions, speckle decorrelation and factors that affect the depth resolution. In Chapter 6, experimental results obtained using the full sensitivity TSI system are presented. A brief description of the samples is followed by the reconstructed depth-resolved cross-sections, including images of samples containing sub-surface features. The chapter goes on to present phase maps and displacement fields of a semi-transparent sample that has undergone rigid body motion. All the displacement components are measured for every voxel in the reconstructed volume. Finally, Chapter 7 summarises the research undertaken and suggestions for related future works are made.

# Measurement of depth-resolved displacement and strain fields using optical methods

#### **2.1 Introduction**

The measurement of displacement and strain fields for experimental mechanics applications is dominated by point and areal measurement techniques. The main ones include the resistive strain gauge [7], fibre Bragg gratings [8], photoelasticity [9], speckle interferometry in all their varieties for in-plane, out-of-plane, slope sensitive and Moiré Interferometry [10]–[14] and digital image correlation [15]–[17]. Areal techniques have achieved a high degree of accuracy and in the best cases are able to measure all the orthogonal components of an object's surface displacement field and all the components of the plane strain matrix [18][19]. Even though it is useful to measure these components, limiting the observational capabilities of the measurement system to just the surface can lead to subsurface problems being missed. Such problems can include delamination in veneers or composite materials [20][21] and the

propagation of stress within granular materials [22][23]. Moreover, subsurface measurements are also used for identification of material properties that are position dependent. Therefore it becomes clear that methods for subsurface measurement become not only useful but necessary. Subsurface measurements of displacement and strain fields can significantly assist in the identification of material properties that are position dependent within the material.

The measurement of displacement and strain fields inside the volume of materials is a challenging endeavour. Over the years, a great variety of techniques were developed to address this problem for different types of materials and with various degrees of success.

A range of techniques have been developed over past few decades in order to measure the internal structure and displacement fields within materials. Examples include threedimensional digital image correlation (DIC) using data acquired from X-ray computed tomography [24]–[26], neutron diffraction [27], phase contrast magnetic resonant imaging (PCMRI) [28] or photoelastic tomography [29][30]. Each technique is based on non-equal physical principles and hence has its own advantages and limitations. For example in DIC the sensitivity is coupled to the spatial resolution, as displacement measurements are evaluated in units of pixels. X-ray diffraction is reliant upon the scattering of an incident wave of x-rays by the electron field [27], neutron diffraction is similar but the scattering is caused by the atomic nuclei in a crystalline material. Magnetic resonant imaging measures the radio frequency signal generated by hydrogen nuclei returning to the equilibrium once a magnetic field is removed. This therefore requires the sample to possess sufficient hydrogen nuclei (usually in the form of fat or water content). X-ray and neutron diffraction techniques are suitable for polycrystalline metals and can be used for the measurement of residual stresses. In the case of many materials that are important to technology or medical applications, such as composite materials or tissues, these methods are either too insensitive, have insufficient spatial resolutions or are not-applicable to the material. Photoelastic tomography is only suitable for materials that exhibit photoelasticity. The use of ultrasound in sonographic imaging is well-known in both biomedical [31] and industrial materials testing applications [32]. By combining this with elastography, ultrasound is also able to be used in the detection of displacement fields of soft tissues [33].

For the purpose of this thesis, the focus of this literature review is mainly on depth-resolved optical measurement techniques that provide displacement or strain fields in the volume of weakly scattering materials (also referred to as "*semi-transparent*" scattering materials). In a

weakly scattering material the number of particles per unit volume is small such that an illuminating wavefront is only slightly perturbed by the material and multiple scattering is minimal [34], where recorded photons have only been scattered only once. The general principles are described along with an overview of the evolution of the subject over the last twenty years. Techniques, such as photoacoustic tomography, that rely on light absorption rather than scattering [35][36], will not be discussed here.

#### 2.2 Depth-resolved optical techniques

#### 2.2.1 Optical coherence tomography (OCT)

Optical interferometry involves the superposition of two coherent wavefronts (object and reference) [14]. A wavefront in the object beam illuminates the sample and the light scattered from it is then recombined with the reference beam before entering the detector. Each of the beams travels a certain path length creating a phase difference between them and thus an interference pattern at the detector. A change in the relative phase between the two wavefronts produces a detectable change in the interference intensity pattern. The path difference must be smaller than the coherence length of the light source in order for the two wavefronts to produce an interference pattern. Low coherence interferometry (LCI) utilises a "white" light source, which has a short coherence length. In LCI, also known as optical coherence-domain reflectometry, the reference arm of the interferometer is equipped with a scanning reference mirror. The axial position of the reference mirror is scanned (known as an A-scan) during the recording of the interferometric signal. Interference is only observed when the reflection delay from the sample matches the reflection delay from the reference mirror within the low coherence length of the light source [37]. The axial position of where an interference signal can be seen (i.e. where the intensity signal is modulated) is known as the "coherence gate". For each scattering point that falls within the coherence gate an envelope modulating a high-frequency intensity signal is detected. The width of this envelope is equal to twice the coherence length (gate) of the source and is a measure of the depth resolution. The movement of the reference mirror allows the reference path length to change so that the coherence gate scans along the depth axis within the sample structure and presents a time

domain interference pattern. Thus when a broadband light source is used to illuminate the sample and the reference mirror is moved along the reference arm this is known as time-domain OCT (TD-OCT). In order to obtain a two- or three-dimensional image, multiple depth scans are necessary. This can be done by performing lateral scans (known as B-scans) in either one or two orthogonal directions.

It was in 1991 that Huang et al first introduced a low-coherence interferometric method to produce depth-resolved two-dimensional cross-sections of biological samples [38] and named it "optical coherence tomography". The authors were able to produce a two-dimensional image by introducing a transverse scan (known as a B-scan) to the sample. Three years later Schmitt et al applied the technique to measure the attenuation and backscattering of light from dense turbid tissues [39] and found it difficult to identify the relationship between the magnitude of the measured OCT signals and the properties of different types of tissues. The authors could not find a clear relationship between the magnitude of the reflected signal and the different regions of a human finger, such as the nail and the dermis. However, the authors concluded that despite this shortcoming, certain features of microstructures embedded several hundred micrometres deep in a turbid tissue could be identified. Schmitt et al also went on to improve the OCT system by enhancing the resolution using multiple light sources and detectors [40]. With the use of an ultrabroadband Ti:sapphire laser, Drexler et al in 1999, obtained ultra-high resolution OCT images [41]. In 2003 Hitzenberger et al developed a method of OCT to produce faster imaging times. This method combines transverse scanning with a confocal scanning laser ophthalmoscope with OCT [42] in order to obtain 64 transverse images of a retina in 1.2 seconds. Aguirre et al conducted an investigation comparing alternative scanning methods [43]: depth priority, transverse priority and en face imaging (perpendicular to the observation direction). The conclusion was that the transverse scanning and en face methods could be used to enable real time imaging to enhance differentiation of tissues. TD-OCT was later used to measure in situ laser ablation when Ohmi et al performed measurements on a human tooth and chicken bone [44].

Phase information obtained by LCI has been used to measure depth-resolved displacements in layered objects [45] and microscopic defects [46] by Gülker et al and Gastinger et al respectively. Gülker et al used a superluminescent diode with a centre wavelength of 840nm and bandwidth of 20nm (a depth resolution of 15.6 $\mu$ m) to record the deformation field in two layers of paint (at the surface and 100 $\mu$ m below it) due to changes in humidity. The authors were able to measure deformations as small as 0.25 $\mu$ m. Gastinger et al used a similar light source to measure delaminations in an adhesive layer  $500\mu$ m thick between aluminium and glass adherends. The authors were able to detect defects 1mm in diameter with a depth resolution of 26.2 $\mu$ m.

#### 2.2.2 Polarisation-sensitive optical coherence tomography (PS-OCT)

Many materials have birefringent properties that are exploited by another OCT variant, Polarisation Sensitive OCT (PS-OCT), to determine stress/strain within materials. In order for an OCT interferometer to be sensitive to the polarisation of the light, it needs to be modified. To ensures that linearly polarised light enters the interferometer, a polariser is used before a non-polarising beamsplitter that divides the input light into the reference and sample arms. A quarter-wave plate is placed in the sample arm angled at 45°, producing an incident object beam that is circularly polarised. The reflected light travels back through the quarterwave plates, giving it an arbitrary polarisation determined by the birefringent properties of the sample. Another quarter-wave plate is placed in the reference arm angled at 22.5°, such that the light is reflected off the reference mirror and passes back through the plate, giving it circular polarisation heading towards the detector. The beams are recombined at the beamsplitter before it is divided again using a polarising beamsplitter with each polarisation being directed onto separate detectors. By dividing the polarisation directions an A-scan will provide information about reflectivity and phase differences between the two orthogonal polarisation components along the z-axis. The phase difference can be used to describe the Stokes vector, a mathematical representation of the intensity, degree of polarisation and shape parameter of the elliptical polarisation.

A low-coherence reflectometer able to detect polarisation-sensitive birefringence was first introduced by Hee et al in 1992 [47]. The authors experimented on a calf coronary artery and demonstrated that variations in phase retardations as small as 0.05° were detectable. De Boer et al took it to the next level by creating a PS-OCT interferometer to obtain two-dimensional OCT images of a bovine tendon [48] by adding a B-scan to the PS-OCT interferometer. A paper by Stifter reviewed a number of forms of OCT, including PS-OCT [49]. The applications of OCT were discussed, with attention being given to imaging in non-medical areas, presenting some of the literature discussed below. Hitzenberger et al used PS-OCT in chicken heart tissue to measure backscattered intensity, birefringence and the orientation of

the fast optical axis in only one axial scan [50]. The intensity and birefringence were measured using the polarisation-sensitive equipment and the phase difference of the orthogonal components of polarisation were used to calculate the fast axis orientation. In 2003 Stifter et al used PS-OCT to map strain fields within glass-fibre reinforced epoxy resin samples [51]. The authors confirmed that birefringence in those materials is caused by anisotropy and stress-induced strain. Pircher et al used PS-OCT on a human cornea and anterior chamber in 2004 [52]. The authors used a transversal scanning method in order to achieve a larger field of view by reducing the number of data points per pixel. This was achieved using lock-in demodulation with a Mach-Zender interferometer to extract the phase difference and thus the Stokes vector. In 2005, Wiesauer et al took Stifter et al's work in 2003 [53] further detailing the calibration process and the measurement of stress/strain in polymer samples quantitatively. The authors also used PS-OCT with markers on the sample to measure increased regions of anisotropy in plastic samples and translucent materials [54] as well as to determine the stress/strain state of materials quantitatively and the orientation of the optical axis. In 2006 Wiesauer et al increased the axial resolution of the PS-OCT system and also performed in-plane strain mapping [55]. In-plane strain mapping was achieved by transversal measurements and the ultra-high resolution was achieved using a femtosecond laser. The authors investigated the relationship between the direction of the internal strain fields and the orientation of the optical axis, which is an indication of the direction of anisotropy in the sample. This was achieved by stretching the sample perpendicular to the slow optical axis, caused by natural anisotropies when unstrained. When externally strained, the slow optical axis direction changes and aligns along with the direction of the applied strain. Hitzenberger et al measured the birefringence in human cornea and also the slow axis orientation using PS-OCT [56]. It was found that adjacent lamellae had orthogonal slow axes, cancelling the birefringences from layer to layer. In 2007 Engelke et al used OCT and PS-OCT to inspect micromechanical gear wheels in a production process, mapping the mechanical stress distributions at the interface between the substrate and the resist [57]. Wiesauer et al demonstrated the use of transversal high-resolution PS-OCT for structural analysis and for mapping stress-related birefringence on non-biological samples [58][59]. The transversal scanning allowed the in-plane strain distribution to be measured.

PS-OCT has been demonstrated to be able to map strain fields within birefringent materials, however it was only the in-plane shear strain that was measured. Other forms of displacement, such as rigid body translation or rotation have not yet been measured and the

technique cannot be used with materials that are not birefringent. With this technology it would be possible to map the out-of plane displacement field, if phase changes were measured from each polarization channel before and after deformation of the sample.

#### 2.2.3 Spectral optical coherence tomography (SOCT)

The previous techniques perform measurements in the time domain; a time varying intensity signal is recorded and then the envelope detection leads to the ranging of internal features within the sample. An alternative approach is to work in the spectral domain, where the frequency of the interference signal encodes the depth of the scattering points. The frequency of the interference signal can be encoded either spatially or temporally. This section focuses on the former case, while Sections 2.2.5 and 2.2.6 do it on the latter.

In spectral OCT, also known as Fourier Domain OCT (FD-OCT), the interference signal is modulated along the spatial axis of a spectrometer sampling a band of wavelengths simultaneously. The object and reference beams are recombined at the beamsplitter and then a diffraction grating spatially separates the different wavelength components onto the pixels on a detector array. By performing a Fourier transform on the detected intensity distribution along the wavenumber axis, the linear scattered amplitude distribution can be reconstructed. If a two-dimensional photodetector array is used whilst an illuminating sheet of light is incident on the sample, all the data from a slice from inside the material is acquired simultaneously, thus negating the need of a movable reference mirror used in TD-OCT and of a scanning device to define a slice. However a B-scan is still necessary for the reconstruction of a three-dimensional sample object.

When optical coherence tomography is combined with microstructure tracking methods such as digital image or volume correlation, as mentioned earlier, the displacement sensitivity is coupled to the spatial resolution. This is not the case if phase changes are used instead, to evaluate displacements. This can be thought of in the change in phase, in terms of the sensitivity vector and the displacement vector. The dot product of these yields a change in the phase and contains no terms relating to the spatial resolution or depth of field:  $\Delta \phi = \mathbf{K} \cdot \Delta \mathbf{r}$  (see Eqn. 3.17).
Fercher et al were the first, in 1995, to report the use of white light and a spectrometer to measure one-dimensional distances within the eye and also the corneal thickness in-vivo along the wavenumber axis (see Section 2.2.5 and 2.2.6 for the literature on wavelength scanning interferometry and tilt scanning interferometry respectively) [60]. White light was scattered from the sample and recombined with the light reflected from a stationary reference mirror before passing through a diffraction grating and onto a photodetector array. The advantage was that no moving parts were required to measure distances as opposed to traditional TD-OCT and the internal microstructure of the object was obtained with the Fourier transform of the measured interference signal. In 2000, Teramura et al [61] and Leitgeb et al [62] applied spectral domain interferometry for use in optical coherence tomography. The authors used a diffraction grating and a cylindrical lens to perform a temporal Fourier transform at the observation plane giving instantaneous measurements of a coherence gated image. The use of Fourier transforms allowed not only object structure reconstruction, but also spectroscopic information such as absorption properties of materials to be measured. Two years later Wojtkowski et al implemented a 5-frame phase shifting technique with complex SOCT [63] in order to reconstruct the amplitude and phase from both the positive and negative optical path differences, caused by the translation of the reference mirror. With this technique, objects of considerable thickness were reconstructed without uncertainty from overlapping mirror images. However, this method was not suitable for invivo measurements as it requires high stability in the sample throughout the duration of the phase shifting. In 2003 Leitgeb et al compared TD-OCT against SOCT [64], concluding that the latter has a sensitivity advantage over the time domain method and a superior signal-tonoise ratio. By linking the optimal bandwidth of the TD-OCT system and the exposure time the author was able to compare the sensitivities of time- and Fourier-domain OCT. The discrete Fourier transform adds to the noise in a FD-OCT system a normalisation factor equal to the reciprocal of the number of samples recorded. That same year, Hauger et al developed a new technique, linear OCT [65], which uses separate fibres to illuminate a stationary reference mirror and the sample. The reflected light is directed to a two-pinhole device which spreads the light onto the image plane to create interference, similar to the Young's slit experiment. This method is an alternative to SOCT but it has a signal-to-noise ratio comparable with that of TD-OCT, which is inferior to that of SOCT. Vakhtin et al developed a SOCT system that used a common beam path for both reference and object beams [66]. This was achieved by placing a glass plate immediately in front of the sample, with the back surface of the glass plate acting as the reference surface. The advantage of this method included the fact that the system is less sensitive to vibrations, the ease of alignment is increased and greater stability due to automatic beam overlap. The reference arm reflectivity is optimised when the interferometer is used to measure samples surrounded by a medium with a refractive index greater than that of air. Yun et al showed that by using a light source at 1310nm it was possible to improve the penetration depth of a SOCT system, imaging a human finger [67]. Cense et al were able to demonstrate high-speed in-vivo imaging of the human retina [68] as were Wojtkowski et al [69]. The authors discovered that by using two ultra-broadband light sources and software dispersion compensation, rates of 29.3 fps at a high resolution were possible. In 2004, Yasuno et al proposed phase-shifting whilst using a tilted reference wavefront in order to remove ghost images due to the autocorrelation term [70]. However the phase shifting algorithm makes it impossible for *in-vivo* samples as this method requires a 5 phase-steps. Szkulmowska et al carried out work to avoid these terms by investigating the optimal conditions of optical power and exposure time [71]. In 2005 Grajciar et al demonstrated that a spatially incoherent light source in a parallel FD-OCT system allows for an efficient suppression of coherent crosstalk giving a superior transversal resolution. The authors found that a light source such as a halogen lamp would be the ideal choice for a parallel detection system but its small output power restricts its use in the fast imaging of biological samples. A review of the different forms of OCT was carried out by Tomlins and Wang in 2005, looking specifically at forms of OCT for three-dimensional noninvasive imaging [72]. Applications of OCT, both current and possible future ones were discussed, with close attention being given to biomedical imaging.

By taking the magnitude of the Fourier transform one can reconstruct the internal microstructure of a sample. The phase change between successive scans can also be used to quantitatively measure displacement. This was demonstrated by De-la Torre-Ibarra et al using phase-contrast SOCT (PC-SOCT) firstly on two independently tilted glass microscope cover slips and then on *ex-vivo* porcine corneas in which the out-of-plane phase changes were measured due to material creep after a step change in the intraocular pressure [73]. This change in phase is related to the displacement in the corneas and deformations with a sensitivity of 420nm per fringe were measured. The same authors went on to measure the simultaneous in- and out-of-plane displacement components in a polymer rubber layer between glass plates [74]. Conventional OCT methods are sensitive to just out-of-plane displacements due to the coaxial illumination and observation directions but by using oblique illuminations with a FD-OCT system, in-plane sensitivity was achieved. By using symmetric

illumination directions two phase differences could be measured (one for each illumination direction) and combined to find the vertical in-plane and out-of-plane displacement components [74].

Doppler OCT (D-OCT) is a method of mapping flow velocity using phase information present in the OCT signal [75]. The phase difference between successive frames and the interframe time are used to determine the rate of fluid flow [76][77]. Vessel diameters as small as 10 $\mu$ m at 2mm below the surface can be imaged *in-vivo* and flow rates of 10 $\mu$ m/s have been detected [78]. The maximum flow velocity is limited by the sampling speed of the system (to prevent unwrapping errors, the phase change between successive frames should not change by more than  $\pi$  radians, to comply with Shannon's sampling theorem). The imaging depth of OCT techniques in tissues such as skin and blood vessels is limited to 1-3mm due to a combination of scattering, absorption, dispersion and, in FD-OCT, to spectral roll-off due to under-sampling.

### 2.2.4 OCT elastography

Elastography refers to a range of techniques that have been developed for the imaging and determination of the mechanical properties of biological tissues [79][80]. The combination of OCT and DIC was first carried out in 1998 by Schmitt demonstrating its effectiveness at measuring internal displacements in biological tissues, including gelatine, pork meat and human skin [81]. 2D image slices of the sample are produced by an OCT system and a speckle tracking algorithm is employed following the mechanical compression of the tissue sample. It was shown that small lateral deformations down to 2-3µm were detectable in human skin and that harder subsurface tissues, such as cysts, are detectable since they affect the deformation pattern. Since then OCT elastography has been used to investigate arterial wall biomechanics [82], atherosclerotic plaques [83] and engineered tissues [84], to name a few. These techniques used 2D cross correlation methods of tracking the speckles, thus limiting its usefulness for when the deformation is large between successive frames. This method of speckle tracking is furthermore limited if the deformation is small such that a speckle only moves by a fraction of a pixel. Kirkpatrick et al attempted to overcome these problems by applying two different methods for speckle tracking [85]. For small deformations, a mean square difference of the lateral shift of the observed features between

adjacent frames was determined. The authors had found that this method performed well for small deformations, with shifts of close to 0.1 pixels recorded for instantaneous speckle shifts and .3 pixels recorded for iterative methods compared to minimum shifts of half a pixel required for previous correlation-based methods [86]. However the iterative method was computationally intensive so as to be unable to perform real time measurements. DIC performs better with shifts close to 0.8 pixels but is limited by speckle decorrelation that is present in larger deformations but this is unlikely between successive frames and gives a high spatial resolution. For larger displacements (greater than 1 pixel) associated with strains, the authors used D-OCT instead. By comparing phases it performs well for measuring displacements around  $\lambda_c/30$  due to its high interferometric sensitivity. The advantage of the OCT method over ultrasound is a significantly improved spatial resolution, allowing more precise characterisation of the tissue physical properties. However OCT elastography is limited by the speckle motion across the detector and therefore determines which of the two approaches to use: By using two approaches, the authors did not have one single standard method for speckle tracking.

#### 2.2.5 Wavelength scanning interferometry (WSI)

Wavelength scanning interferometry, also known as wavelength-tuning interferometry (WTI), frequency scanning interferometry (FSI) or swept-source OCT (SS-OCT), is now an established optical technique used in profilometry and tomography. Like OCT it uses multiple wavelengths to illuminate a sample but, unlike spectral OCT, the wavelengths are presented sequentially rather than simultaneously [38][87]. The phase difference between the wavefront reflected from a reference surface and that from a slice within the sample is due to the optical path differences between the reference and object beams. This phase difference is related to the central wavelength and also the wavelength tuning range. A sequence of interferograms is obtained simultaneously with the tuning of the wavelength of the laser and the sample cross section can be reconstructed from the magnitude of a 1D Fourier transform along the wavenumber axis. This method can also be used to measure sample displacements by measuring changes in the phase between consecutive acquisitions.

WSI is effectively an alternative implementation of OCT, first proposed by Fercher et al in 1995 [60] and has been developed and utilised by many others since. As in SOCT, the depth

resolution in WSI is decoupled from the displacement sensitivity and has a superior signal-tonoise ratio since low frequency noise can be easily filtered out. This technique has been investigated for use in profilometry by Kuwamura and Yamaguchi [88], who produced a twodimensional surface profile interferogram to measure a step of 0.15mm height; measurement of absolute distances by Coe et al and Gibson et al [89][90] as well as ophthalmic imaging by Lexer et al [91], who produced a one-dimensional frequency spectrum to determine intraocular distances. At the same time Chinn et al were developing a system using a narrowband source swept quickly enough over a large bandwidth so that in-vivo measurements could be obtained [92]. The large bandwidth gives a better depth resolution and the faster sweep allows faster data acquisition with a rate of 25nm in 100ms. In 2000, de Groot looked into a 13-frame phase shifting algorithm in order to reduce the unwanted interference caused by reflections from the back surface of transparent plates [93] and thus being able to look at the front surface with reduced noise. Three years later Choma et al conducted a study comparing: a) FD-OCT, where the light source is broadband and the system utilises a diffraction grating to disperse the combined reflections from the sample and the reference beams; b) WSI, where the light source is tuned through its bandwidth; c) and time domain OCT [94]. The authors concluded that FD-OCT and WSI have a superior sensitivity and signal-to-noise ratio over time-domain OCT. Hibino et al [95] proposed new sampling algorithms for the recorded interferograms to overcome the frequency shifts caused by the refractive index dispersion of the sample and other non-linearities within wavelength scanning, such as power variations of the light source and nonlinearities of the PZT transducer of the external cavity. By carefully choosing the distance between the sample surface and the reference surface multiple reflections could be tuned to appear at specific harmonic frequencies which could then be removed. The authors used WSI to measure the thickness of a sample as well as the surface profile simultaneously.

Similar to FD-OCT, obtaining phase information before and after the deformation of a sample can lead to the determination of displacement/strain components. In 2004 Ruiz et al used WSI for just such a purpose, measuring displacement fields of multiple glass-air interfaces using smooth wavefronts [96] and then later in 2005 with speckle fields from semi-transparent scattering surfaces [97]. By using the Fourier transform the authors were able to reconstruct an image of the sample cross-section and by using the changes in phase distribution, measure the depth-resolved out-of-plane displacements of independent scattering surfaces due to a controlled tilt. In 2008, Hwang et al [98] put forward a new method of

obtaining superior phase information from WSI to measure both the surface profile and thickness of a sample. Unlike others who obtained the phase using a Fourier transform, the authors used the wavelet transform. This enabled the nonlinear phase term, produced by the total phase difference between reflected beam and incident beam due to multiple reflections of the thin film sample [99], to be obtained with a very small phase error. Though the authors determined the phase information, it was only used for surface profilometry. However it could be used to measure displacement by evaluating the phase difference before and after deformation of a sample, such as that demonstrated by Chakraborty and Ruiz in 2012 [100]. Full sensitivity 3D displacement fields were measured in an epoxy resin block by using three non-coplanar illumination directions. Displacements of the order 0.14µm laterally and 32.5nm axially were reported. However, the authors warned that material dispersion and optical absorption are issues that require further investigation.

## 2.2.6 Tilt scanning interferometry

It has been discussed earlier in this chapter how broadband light and wavelength scanning has been used to image depth-resolved structures. Due to the wide range of frequencies present in the light source, frequency absorption and index dispersion problems arise. This is especially problematic in biological tissues and other dispersive materials, when samples have a high variability and inconsistent spectral responses. The study by Hammer et al showed how the refractive index of light changes over a range of wavelengths in ocular materials [101]. It was found that the refractive index of bovine vitreous humour is 1.345 and 1.328 at wavelengths of 430nm and 1000nm respectively. When broadband light enters a sample rather than a reflective surface, the difference in the propagation speeds of the wavelengths lead to a change in the relative phases arriving at the detector and therefore additional frequencies are introduced in the spectral domain. This has the effect of broadening the point spread function (psf) and hence a degradation the spatial resolution. A monochromatic light source can overcome the dispersion problems and by selecting the wavelength to match the sample's low-absorption spectrum, measurements can be performed on a wider range of samples.

Unlike OCT or WSI, tilt scanning interferometry uses only one wavelength and is based on continuously scanning the incident angle of the illumination beam using a tilting mirror. TSI is proposed by Ruiz et al in 2006 [6] for measuring three-dimensional displacement fields

within weakly scattering samples. It can be regarded as an extension of the tilting wavefront speckle profiling/contouring technique demonstrated by Rodriguez-Vera et al [102]. As with PC-SOCT and WSI, the displacement sensitivity is decoupled from the depth resolution of this technique.

TSI works by recording a sequence of speckle interferograms of an object whilst the illumination direction of a monochromatic illumination beam is continuously changed. The illumination tilt introduces a position dependent phase shift whose temporal gradient, i.e. the interference frequency, encodes depth information. Performing a 1D Fourier transformation along the tilting angle axis and then taking the magnitude reconstructs the object microstructure.

The principle of the technique was successfully demonstrated by measuring deformation fields inside the volume of an epoxy resin beam undergoing three-point bending. The authors in [6] demonstrated that by illuminating the object from equal and opposite azimuths, the horizontal in-plane and the out-of-plane sample displacements could also be determined by combining the phase changes obtained before and after deformation for each illumination direction. Left and right illumination 'reference state' sequences were acquired followed by left and right 'deformed state' sequences. Taking the phase from the 1D Fourier transform allowed the evaluation of the optical phase for each pixel and hence of the three-dimensional phase-change volumes for left and right illuminations. The out-of-plane and the horizontal in-plane displacements were obtained, respectively, from the sum and the difference of these phase-change volumes.

As described in Section 2.2.5 and also the previous paragraph the processing of the data was performed using a 1D Fourier transform. Another approach towards tomography is by considering them as linear filtering operations [103]. The linear filtering operation works by considering the source distribution of the system and creating an appropriate vector representation of the illumination and observation in k-space, where k refers to a wavenumber vector.

Figure 2.1(a) shows a simple TSI optical setup, highlighting the tilt of the incident illumination beam and the scattered light being collected on a CCD photodetector array. The relationship between incident and reflected wave vectors leads to the creation of a spherical shell, known as an Ewald sphere as shown in Fig. 2.1(b), with  $\mathbf{k}_i$  and  $\mathbf{k}_o$  representing the illumination and observation wave vectors respectively. The magnitude of each of these

vectors is equal to  $2\pi/\lambda$  and since  $\lambda$  is constant in a TSI system, the magnitudes of  $\mathbf{k}_i$  and  $\mathbf{k}_o$  are equal.



Figure 2.1. Three-dimensional k-space representation of a TSI system. (a) When light is incident at central angle  $\theta_{\rm C}$  onto object O and the illumination beam tilts through a range  $\Delta \theta$ , the scattered reflected light is imaged by the imaging lens onto the CCD detector. (b) The Ewald sphere representation.  $\mathbf{k}_{\rm i}$  and  $\mathbf{k}_{\rm o}$  represent the illumination and observable wavevectors respectively forming an area on the surface of an Ewald sphere, known as the transfer function. Figure is from Ref. [103].

The sensitivity vector of the system, **K**, can be defined as  $\mathbf{K} = \mathbf{k}_i - \mathbf{k}_o$ . Accounting for the numerical aperture of the detector the measurements are detected over a finite area of the Ewald sphere surface and this area is known as the transfer function (shaded in grey at the top of Fig. 2.1(b)). By performing an inverse 3D Fourier transform on the transfer function, the system's 3D impulse response, or point spread function, in the space domain can be found. If this point spread function is convolved with the object function (the ideal representation of the object microstructure, independent of the wavelength), then the reconstructed object microstructure is obtained. Furthermore, both lateral and axial resolutions could also be determined from the transfer functions.

Other optical measurement techniques share similar features in that information is collected by illuminating an object and then detecting the light scattered from it. The main differences distinguishing each technique can be narrowed down to the method of scanning or illuminating the object and then the method used to detect the scattered light. Coupland and Lobera applied this approach in order to characterise several three-dimensional optical techniques and were able to numerically compare the performance of monochromatic and polychromatic tomography [104]. This approach of using the system impulse response was later applied to TSI by Galizzi et al in 2009 [105]. Using modelled data the authors simulated a 3D displacement of a multilayer sample. The ability to detect the internal structure of the sample object and accurate detections of the three-dimensional displacement was demonstrated. In 2010 Galizzi et al highlighted the advantages of the linear filtering approach over traditional 1D Fourier transforms when applied to TSI [106]. A scatterer acting as a point source was positioned at the origin of the coordinate system and therefore the reconstructed object is equal to the point spread function of the system. After evaluating this system's impulse response, two scatterers were positioned on the same axial plane as the first point source. Employing the linear filtering operation, the two scatterers were clearly reconstructed as two points in the same positions. The authors concluded that with this method of detection, each scattering point in the same axial layer can be resolved in the same axial slice from the data volume. The traditional 1D Fourier transform method is unable to do this in TSI as a 'tilted' reconstruction is produced and requires re-registration. Another advantage of k-space processing is that each individual depth slice within the sample can be digitally focussed, allowing an unlimited depth-of-field.

### 2.2.7 Angular spectrum scanning

Where TSI uses a tilting mirror to alter the incident angle of illumination, angular spectrum scanning uses a spatial light modulator (SLM). First proposed by Duan et al in 2006 [107], the idea of this method is based on the phase difference between two rays arriving at the same point on a detector: one ray is reflected from the sample surface, the other ray is reflected from a reference mirror beneath the sample, as shown in Fig. 2.2. This phase difference is related to the angle of incidence of the illumination beam and the height of the sample surface; it is equal to the dot product of the propagation vector and the height vector.

The alternative method to determining the phase difference is to alter the incident angle whilst using a single wavelength. Figure 2.3 shows how this can be represented in k-space.

The propagation vector (k-vector or wave vector),  $\boldsymbol{k}$ , has a magnitude proportional to the optical frequency with an angle  $\theta$  to the height vector,  $\boldsymbol{h}$ , which lies on the polar axis.

If  $\theta$  changes the radius of the Ewald sphere will remain constant since the magnitude of k never changes and therefore the optical frequency will also remain constant. Scanning  $\theta$  through a given range, the height component,  $k_h$ , will change and the sample profile height can then be determined since it is proportional to the rate of change in the phase with respect to  $k_h$ .

A cone of vectors is produced when the azimuth is changed and by placing spatially incoherent point sources at the tip of these vectors, creating a 'ring source' on the Ewald sphere surface, the authors were able to tune the angular spectrum by tuning the radius of the ring source. A range of k-vectors with equally spaced height components was labelled the spatial frequency comb (SFC) and yields a set of coaxial ring sources in the  $k_{\perp}$  direction (the lateral component of k).

The SFC is very sensitive to misalignments in the reference mirror. When the reference mirror is not perpendicular to the optical axis the height vector, h, therefore does not lie on the polar axis. The height components of the k-vector,  $k_h$ , then become unevenly spaced and the concentric ring sources act as a broadband source due to a single radius having multiple height components in the spatial frequency comb. However this can be corrected by using eccentric ring sources to create a new spatial frequency comb with evenly distributed lateral k-vector components with h lying off the polar axis. This allows the control of the direction of the depth sensitivity. The authors demonstrated a proof-of-principle experiment, using angular spectrum scanning to perform surface profile measurements on a step sample, using a computer-controlled spatial light modulator and a rotating ground glass plate to construct the ring source to control the incident angle of the illumination beam. With this setup, a step surface profile was measured with an error of 0.02mm. The authors furthered their work and improved the performance of the SFC by implementing a spatial frequency comb of 'fireworks' (SFCF) in place of the singular ring source [108].



Figure 2.2. The angular spectrum scanning optical setup. Laser light is expanded before passing through a liquid crystal spatial light modulator, LC-SLM and a rotating ground glass plate, GG. This produces a spatially incoherent 'ring source' that is then reflected onto the sample, GB. Light is scattered and recombined with a reference beam from mirror  $M_R$  before it is imaged onto the CCD detector. Figure is from Ref. [107].



Figure 2.3. k-space vector representation of angular spectrum scanning. When  $\theta$  changes, the radius of the 'ring source' changes and therefore so does the height component of the propagation vector  $\mathbf{k}_{\rm h}$ . In order to gain a constant rate of change in  $\mathbf{k}_{\rm h}$ , a spatial frequency 'comb' is created by adjusting the radius the ring source accordingly. Figure is from Ref. [108].

They discovered that an ideal SFC with uniform comb heights cannot be created if the thin ring sources have the same thickness and irradiance. What is instead produced is a tapered comb with comb heights that vary according to the size of the ring source. While it is possible to adjust the thickness or the irradiance of the ring sources, this creates its own set of drawbacks: By adjusting the thickness, the inner rings become too thick to function as an ideal ring source for the comb spectra; and by adjusting the irradiance a precise control over the grey levels in the SLM is required. Thus the authors came up with the SFCF: An array of 18 discrete point sources in an arrangement resembling a bursting firework. This improved the consistency of the comb vector heights in k-space, allowing for more uniform ring sources and solving shadowing problems.

Angular spectrum scanning is free from moving parts, except for a rotating ground glass required in order to produce the spatially incoherent ring source. Furthermore the direction of the sensitivity vector can be controlled. Considering the system in a k-space vector representation the height/sensitivity vector is usually normal to the sample surface and the system is therefore sensitive to out-of-plane displacements. By controlling height vector direction this allows in-plane displacements to be measured, in addition to out-of-plane. So far angular spectrum scanning has not been used for tomographic imaging or displacement measurement, unlike TSI.

#### 2.2.8 Lauer microscopy

TSI and angular spectrum scanning are techniques that measure light backscattered from a sample. In 2000, a prototype tomographic microscope was developed by Lauer [109][110] that works in a similar fashion to TSI but detects the forward scattering light from a sample as shown in Fig. 2.4. A monochromatic illumination beam is directed, via a tilting mirror, and focussed onto a sample. This illumination beam is forward scattered and is focussed onto a detector located at the Fourier plane. The sample is scanned by altering the incident illumination angle and the scattered light is recorded by a detector array. The intensity distribution at a given pixel corresponds to a given spatial frequency of the combination of the wave observed scattered by sample and also of the illumination beam that passes through it. This frequency is a component in the Fourier transform of the sample structure and by recording for a set of frequencies the object can be reconstructed using a 3D inverse Fourier

transform. The reference beam also incorporates a phase-shifting mirror allowing for the acquisition of complex data from samples with both phase and absorptive structures.

Lauer's prototype was used to image biological samples such as cells, flies wings and bacteria with a depth of field of approximately  $40\mu m$  and a resolution limit of a quarter of a wavelength.



Figure 2.4. The Lauer microscopy optical setup. The light is split with the illumination beam being directed onto the sample via a tilting mirror in a forward scattering configuration. The light is recombined at beam splitter B2 and falls onto the detector. Figure is from Ref. [110].

In 2008, a similar microscope was used by Simon et al to compare 'tomographic' images of cellular algae and pollen grains, i.e. multiple illumination angles, with 'holographic' images from a single illumination angle [111][112] and also by Debailleul et al [113]. Results showed that tomographic microscopy produced images with superior resolution in both lateral and axial directions. Since an object imaged in a hologram contains out-of-focus parts giving it a blurred looked, tomography is able to overcome this problem by reconstructing the object as a number of slices. Furthermore the tomographic microscope it becomes also able to highlight structures within a cell that were not visible in the holographic images. If one considers the vector representation of the tomographic microscope it becomes apparent that under the current setup the direction of both the illumination and observation vectors are the same. This is due to the forward scattering layout and therefore the resultant sensitivity vector is cancelled out due to them having the same magnitude and direction. This then leaves the depth and lateral resolutions to be solely dependent on the numerical aperture of the imaging lens.

## 2.3 Comparison of SOCT, WSI, TSI and angular spectrum scanning

A comparison of depth-resolved optical measurement techniques was carried out by Huntley and Ruiz in 2011 [114]. SOCT is a technique that uses a broadband source and therefore presents the multiple wavelengths simultaneously. Considering SOCT as a linear filtering operation the magnitude of the k-vectors vary with each wavelength present leading to multiple Ewald spheres with differing radii, and this is the cause of the dispersion problem in certain materials. WSI also uses multiple wavelengths, though presented sequentially. The larger the spectral bandwidths of the light source, the larger the axial size of the transfer function in k-space. The spatial resolution of an optical system is inversely proportional to the dimensions of the transfer function. In whole-field optical systems only the scattered light that falls within the numerical aperture of the imaging lens is detected. Therefore in a system where the illumination beam is parallel to the optical axis the lateral resolution of these systems is proportional to the numerical aperture of the imaging lens. TSI, Lauer microscopy and angular spectrum scanning are techniques based on the use of multiple incident illumination angles. Due to the change in incident angle throughout the duration of a scan, the direction of the incident vector changes and therefore the scattering vector changes accordingly, as in Fig. 2.1(b). This creates a larger lateral transfer function area on the Ewald sphere surface, depending on the range of tilt used: The larger the range the larger the lateral size of the transfer function and therefore the better the lateral resolution. In the case of TSI the tilting range also affects the shape of the transfer function and thus affects the depth resolution in the same way [103]. Furthermore, in a tilting incident wavefront technique, the central incident angle affects the direction of the sensitivity (kvector). In TSI the incident wavefronts are not parallel to the optical axis. This allows the system to be sensitive to not only out-of-plane displacements but also in-plane. In the case of angular spectrum scanning the height vector can be adjusted to the user's requirements and therefore the system can be adjusted to be sensitive to the measurements of both in- and outof-plane measurements. When using a Lauer microscopy system the central incident angle lies on and parallel to the optical axis. As mentioned in Section 2.2.8, the magnitude of the resultant scattering vector  $(\mathbf{k}_i - \mathbf{k}_o)$  is zero due to the forward scattering nature of the system.

In both PC-SOCT and WSI the depth resolution is dependent on the bandwidth of the light source: The larger the bandwidth, the better the depth resolution. In the case of the tilting wavefront techniques, since they utilise a monochromatic light source, the depth resolution is dependent on the tilting range of the illumination beam. In all cases the depth range is directly proportional to the number of illumination angles used.

In Ref. [103] a comparison of these depth-resolved optical techniques was performed. By considering each technique as a linear filtering operation the authors were able to directly compare the axial and lateral resolutions by representing them in k-space, determining the system transfer functions, then finding the dimensions of the system point spread functions and therefore the system spatial resolutions.

## 2.4 Summary

Depth-resolved optical techniques have been presented and examined, with a focus on those that are able to measure displacement fields or strain distributions for applications in biomedical or mechanical engineering. The main technology in depth-resolved optics is optical coherence tomography in its many forms; however the focus of research tends to be more on the imaging of a sample's internal microstructure with *in-vivo* measurements being performed with an axial resolution of  $1\mu$ m. Spectral OCT has the advantage that no moving parts are required to perform an A-scan and has a superior signal-to-noise ratio. It has been demonstrated to be able to reach axial resolutions down to 2.1µm as well as perform *in-vivo* imaging of a human retina. Wavelength scanning interferometry is another well-known and popular technique used in imaging and this too also has a superior signal-to-noise ratio over time domain OCT. The axial resolutions of OCT, WSI and SOCT require a light source capable of producing multiple wavelengths. The axial resolutions are dependent on this bandwidth with the relationship being inversely proportional.

The use of techniques utilising multiple wavelengths for imaging is well-known and they have been utilised for the purpose of displacement mapping. Out-of-plane displacements of 250nm, 420nm and 150nm have been achieved using OCT [45], SOCT [73] and WSI [100] respectively. PSOCT has been used extensively in the mapping of subsurface strain fields however this technology requires a birefringent sample. Furthermore, small strains are not easily detectable due to the small optical path in the samples (~<3mm), over which both polarization components develop a phase delay proportional to the principal strain difference. OCT has been combined with digital image correlation to produce depth-resolved displacement mapping and is known as OCT elastography. Even though subpixel displacements can be measured, the spatial resolution is degraded (due to the size of the subvolumes used to evaluate the correlation) and the displacement sensitivity depends on the FOV. Full sensitivity displacement measurements have been performed using symmetric illumination directions in WSI and SOCT, with potential drawbacks of dispersion and absorption problems.

Single-wavelength techniques have also been shown to be able to image sample profiles and sub-surface microstructure. The problems associated with dispersion and absorption disappear, while the spatial resolution is limited by the scanning range. Angular spectrum

scanning has so far been used in profilometry applications and Lauer microscopy is unable to provide displacement information due to the forward scattering configuration. However both in- and out-of-plane deformations have been measured using tilt scanning interferometry. A backscattering configuration combined with symmetric illuminations will be able to provide full sensitivity 3D measurements.

The next chapter will examine TSI in more detail, including: 1) working principle, 2) reconstruction of the scattering media, 3) depth range and depth resolution, 4) phase and displacement measurement and 5) an overview of the prototype system presented in Ref. [6].

# Chapter 3

# Tilt scanning interferometry

# **3.1 Introduction**

In the previous chapter, the main optical techniques that were proposed to measure displacement fields inside the volume of weakly scattering materials were summarised. It was also mentioned how various disciplines in the field of experimental mechanics could benefit from this ability, including identification of material constitutive parameters [81], study of damage, fracture in adhesives [46][115] and biomechanics of tissues [116], to name a few.

This chapter will introduce tilt scanning interferometry as it was originally proposed in 2006, i.e. as a technique that provides depth-resolved microstructure and displacement fields (using the optical phase) within the volume of semi-transparent scattering materials. The first prototype provided horizontal in-plane and out-of-plane sensitivity along one axis with a depth resolution of ~1mm and a depth range of ~10mm, a remarkable ability given the simplicity of the setup. Further developments of the TSI first prototype promised great rewards. The natural extension to that work, and the aim of this research, was to focus on the following aspects of the technique:

1) **Sensitivity**: To make it truly a full sensitivity system so that it provides all orthogonal components of the 3-D displacement field (both in-plane and the out-of-plane components).

2) **Depth-resolution and data throughput**: To increase the axial resolution to resolve submillimetre features and also increase the size of the data-volume.

3) Errors: To reduce reconstruction and displacement errors due to: a) signal non-linearity,b) detector bit depth, c) loss of signal modulation, d) speckle decorrelation, e) repeatability and d) sample loading configurations.

In Section 3.2 the principle of TSI is explained, followed by a description of the first prototype in Section 3.3.

## **3.2 Working principle**

### 3.2.1 Depth encoding by a tilt-induced carrier frequency

Figure 3.1 shows a semi-transparent scattering material of refractive index  $n_1$  immersed in a medium of refractive index  $n_0$ , illuminated by a collimated beam of wavelength  $\lambda$  (wavenumber  $k=2\pi/\lambda$ ) at an angle  $\theta_0$  to the optical axis of the system. The illumination beam is refracted at the object surface (regarded as flat for simplicity) and is scattered at a point with coordinates (x, y, z) within the material. The scattered light is then recombined coherently with a reference beam R which comes from the same light source, and is then imaged onto a two-dimensional photodetector array.



Figure 3.1. Principle of Tilt Scanning Interferometry: As the illumination angle changes, the interference signal is modulated by a position-dependent frequency.

Equations (3.1) to (3.6), (3.8), (3.10) and (3.12) to (3.14) were taken from Ref. [6]. The phase difference between the scattered light and the reference beam can be expressed relative to the phase at the origin (0, 0, 0) as:

$$\phi(x, y, z) = \phi(0, 0, 0) + k[n_0 x \sin \theta_0 + n_1 z (1 + \cos \theta_1)]$$
(3.1)

During a scan, if the illumination angle  $\theta_0$  changes linearly with non-dimensional time *t* about the centre angle  $\theta_c$ , i.e.

$$\theta_0(t) = \theta_C + \theta_0 t \tag{3.2}$$

where  $\dot{\theta}_0$  is the angular velocity  $\delta\theta_0 / \delta t$  with  $\delta\theta_0$  representing the incremental tilt angle and  $\delta t$  being the number of successive frames between tilt increments ( $\delta t = 1$ ). *t* ranges from  $-\Delta\theta_0 / 2\delta\theta_0$  to  $+\Delta\theta_0 / 2\delta\theta_0$ , where  $\Delta\theta_0$  is the total tilting range. By evaluating the time derivative of the phase in Eqn. (3.1),  $d\phi/dt=2\pi f$ , we obtain a non-dimensional temporal frequency (units of cycles per frame):

$$f(x, y, z, t) = f(0, 0, 0, t) + \frac{kn_0}{2\pi} \dot{\theta}_0[x\cos\theta_0(t) - z\xi(t)]$$
(3.3)

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f(0, 0, 0, t) represents the carrier frequency observed at the origin of the Cartesian coordinate system in Fig. 3.1. The frequency of the second term in Equation (3.3) varies with x and z and accounts for the optical path difference between (0, 0, 0) and the scattering point at coordinates (x, y, z) within the sample. The refraction parameter  $\xi$  is defined as:

$$\xi = \frac{\chi \cos \theta_0 \sin \theta_0}{\sqrt{1 - \chi^2 \sin^2 \theta_0}}$$
(3.4)

with  $\chi = n_0/n_1$ .

As in OCT and related techniques, it is assumed that the interference contributions from multiple scattering within the material can be neglected. The intensity signal due to the interference between light coming from all the scattering points along a line parallel to the optical axis at (x, y) in Fig. 3.1 and the reference wavefront is modulated with multiple frequencies as follows:

$$I(m,n,\theta_0(t)) = A_r^2(x,y) + 2A_r(x,y) \int_{z_1}^{z_{max}} A_z(x,y,z) \cos[2\pi f(x,y,z)t] dz + 2 \int_{z_1}^{z_{max}} \int_{z_1}^{z_{max}} A_z(x,y,z) A_{z'}(x,y,z') \cos\{2\pi [f(x,y,z) - f(x,y,z')]t\} dz dz'$$
(3.5)

 $A_o(x, y, z)$  represents the amplitude of the object wave originating from a small volume element centred on (x, y, z), which is imaged in turn onto pixel (m, n). If  $p_x$  and  $p_y$  represent the pixel pitch along the x and y axes on the photo-detector array, then  $x=Mnp_x$  and  $y=Mnp_y$ , with M the magnification of the imaging system. While the first term in the right hand side of Eqn. (3.5) represents the DC component of the reference beam, the second term corresponds to the modulation due to interference between the reference beam and light scattered within the material. The integration limit  $z_{max}$  represents the object back surface. The double integral in the third term is due to interference between light scattered from various points within the object and adds to the DC and low frequency components in the interference signal.

The TSI process can be thought of as a series of procedures as described in Fig. 3.2 with the acquisition of the intensity signal over a tilting scan being described in Fig. 3.2(a).



Figure 3.2. The complete TSI process in 3 steps. The raw data is collected in step (a) and the final reconstructed depth-resolved object is the output at the end of step (c).

### 3.2.1 Reconstruction of the scattering microstructure

A one-dimensional Fourier transform of the intensity signal I(m, n, t) along the time axis gives rise to a spectrum with peaks that resemble the object internal refractive index transitions. There is a DC peak at f = 0 for all x. When an opaque surface is imaged with this TSI approach, the autocorrelation term cannot be distinguished from the DC term as the scattering layer has negligible thickness. On a weakly-scattering sample, the autocorrelation term appears close to the DC peak but with lower amplitude. The position of the peaks is therefore linked to the internal structure of the object, whereas their amplitudes are related to the degree of scattering or reflection coefficient at each point within the object. Since the peak positions correspond to the object structure, this stage of the TSI process corresponds to Fig. 3.2(b). The object can be viewed as a sequence of thin layers within which optical properties do not change, in which case the integrals can be written as discrete sums in Eqn. (3.6). The Fourier transform of Eqn. (3.5) can thus be written as:

$$\widetilde{I}(f) = A_r^2 \widetilde{W}(f) + A_r \sum_{z=1}^{N_s} A_z \exp(\pm i\phi_z) \widetilde{W}(f \pm f_z) + \sum_{z=1}^{N_s} \sum_{z'=z+1}^{N_s} A_z A_{z'} \exp[\pm i(\phi_z - \phi_{z'})] \widetilde{W}[f \pm (f_z - f_{z'})]$$
(3.6)



Figure 3.3. Fourier transform of the intensity at a given pixel on the detector. Regions 1, 2 and 3 correspond to the three terms on the right hand side of Eqn. (3.6) respectively.

where  $\tilde{I}(f)$  is the Fourier transform of the intensity;  $A_r$ ,  $A_z$  and  $A_z$  are the distributions of the scattered amplitude from the reference beam and scattering layers z and z' respectively;  $\tilde{W}(\hat{f})$  terms represent the Fourier transform of window function W(t) used to sample the intensity signal I(t) in Eqn. 3.5;  $N_s$  is the number of discrete thin layers within the sample;  $\phi_z$  is the phase difference relative to the reference wave. The first term on the right hand side of Eqn. 3.6 represents the DC component and can be seen as the large peak around frequency f=0 on Figure 3.3. The third term with the two summation operators is the autocorrelation term, representing interference between scattering points within the sample, and is viewed as low frequency noise close to the DC peak in region 3. The second term containing the single summation operator is the cross-correlation between the reference beam and the object beam, and represents the sample in region 2.

Eqn. (3.2) shows how  $\theta_0$  changes during the course of a scan and since the refraction parameter in Eqn. (3.4) depends on it, its value therefore changes during the course of the scan. The consequence of this is that the frequency in Eqn. (3.6) is not linearly related to position: If there was a linear relationship, the frequency spectrum analysis of the intensity signal would reveal the internal microstructure with a proportional relationship between frequency, lateral position and depth. Depending heavily on the central illumination angle and the refractive indices ratio  $\chi$ , it was shown in Fig. 4 in Ref. [6] that for a central angle  $\theta_c$ =  $\pi/4$  and  $n_1/n_0 > 1.4$ ,  $\xi$  is almost constant (actually a shallow maximum) inside the material during a scan around  $\theta_c$  due to the small mirror tilting range. In this case there is a frequency component that appears to vary linearly with depth and in this sense the central illumination angle  $\theta_c = \pi/4$  is optimal. Light reaching the surface of an opaque surface in air, however, did not suffered refraction at any intermediate interface To represent this we set  $n_1 = n_0$  and therefore Eqn. (3.4) gives  $\xi = \sin(\theta_0)$ . In this case the position-encoding frequency in the second term of Eqn. (3.3) shows a non-linear behaviour around  $\theta_c = \pi/4$ , due to the  $\cos(\theta_0)$  and  $\sin(\theta_0)$  terms (and not due to a divergence in the illuminating beam as discussed in Section 5.4.3), which leads to a 'shift' in the instantaneous frequency f(x, y, z, t) as the scan progresses. This frequency chirp has a detrimental effect on the depth resolution and needs to be reduced or compensated for in order to improve the reconstruction of the object structure. It is then expected that the chirp would be more deleterious for surface measurements in profilometry applications, while less so when imaging depth-resolved structures in materials for which  $\xi$  has a maximum at  $\theta_c$ . Chirp removal and re-registration are discussed in detail in Chapter 4.

#### 3.2.3 Depth range and depth resolution

The depth z of a scattering point underneath the object surface can thus be obtained from Eqn. (3.3) by evaluating the 'average' frequency through the whole scan, rather than instantaneous frequencies, as:

$$z(x,y) = \frac{1}{\xi} \left\{ x \cos \theta_0 - \frac{2\pi \left[ \left\langle f(x,y,z,t) \right\rangle - \left\langle f(0,0,0,t) \right\rangle \right]}{k n_0 \dot{\theta}_0} \right\}$$
(3.7)

where  $\langle \rangle$  indicates average, z represents the centroid of a particular peak in the frequency domain after the Fourier transform. The spectral bandwidth  $\Delta f$  associated with a thickness  $\Delta z$  within the object can be obtained using Eqn. (3.7) in units of cycles per scan duration, as:

$$\Delta f = \left| -\frac{n_0 |\xi| \Delta \theta_0}{\lambda} \Delta z \right|$$
(3.8)

The amplitude distribution of the scattered light is obtained by a mapping of the modulation amplitude  $|\tilde{I}(m,n,f)|$ , with ~ indicating Fourier transformation, from spectrum coordinates (m, n, f) into spatial coordinates (x, y, z) through the relationship between frequency and position shown in Eqn. (3.7). For a sample with refractive index  $n_1 = 1.6574$  surrounded by air,  $n_0 = 1$  and illuminated with central angle  $\theta_C = \pi/4$ , solving Eqn. (3.4) yields  $\xi = 0.3336$ . If  $\Delta \theta_0 = 25$ mrad and  $\lambda = 532$ nm, then Eqn. (3.8) shows that a spectral bandwidth of 10 cycles per scan duration gives a sample thickness of 638µm.

The depth resolution is defined such that the frequency difference  $\Delta f$  between two neighbouring peaks is at least twice the distance from their centres to their first zero. A rectangular window W(t) of duration T results in a sinc function of width  $\Delta f = 2/T$  in the frequency domain, whilst a Hann window, defined as:

$$W(t) = 0.5 \left[ 1 - \cos\left(\frac{2\pi t}{T - 1}\right) \right]$$
(3.9)

has a spectral width  $\Delta f = 4/T$ , i.e. double the width of the spectrum from a rectangular window and therefore it has the effect of halving the resolution. From Eqn. (3.8), the depth resolution is therefore:

$$\delta z = \gamma \frac{\lambda}{n_0 |\xi| \Delta \theta_0} \tag{3.10}$$

where  $\gamma = 2$ , 4 for rectangular or Hann windows, respectively. The lateral resolution,  $\delta x$ , is given by the average size of a speckle on the object is given by

$$\delta x = \frac{1.22\lambda(1+m)}{NAm} \tag{3.11}$$

where NA is the numerical aperture and *m* is the magnification of the imaging lens.

Equation (3.1) shows the instantaneous phase difference between the scattered light from the sample and the reference beam. However the temporal phase change during the scan will be

$$\frac{\partial \phi(x, y, z, t)}{\partial t} = \frac{\partial \phi(0, 0, 0, t)}{\partial t} + \frac{\delta \theta_0}{\delta t} k \left[ x n_0 \cos \theta_0 - n_1 z \sin \theta_0 - z \xi \right]$$
(3.12)

The total phase change over the entire scan duration introduced by a wavefront coming from a point within the sample over a tilting range  $\Delta \theta_0$  is given by

$$\Delta\phi(x, y, z) = \Delta\phi(0, 0, 0) + k\Delta\theta_0 \left[xn_0 \cos\theta_0 - n_1 z \sin\theta_0 - z\xi\right]$$
(3.13)

There will be  $|\Delta \phi| / 2\pi$  modulation cycles introduced in the interference intensity signal by the total phase change. According to the Shannon sampling theorem, the number of samples (frames),  $N_f$ , needs to be at least twice the number of modulation cycles, i.e  $N_f \ge \Delta \phi(x, y, z) / \pi$ . The depth range,  $\Delta z_{range}$ , is defined as the maximum depth a slice can be situated within the sample in order for it to be possible to determine its displacement, and for a given central illumination angle this is defined by  $N_f$ , and is given by

$$\Delta z_{range} \approx -\frac{\lambda}{2n_0 \xi \Delta \theta_0} \left( N_f - \frac{\Delta \phi(0,0,0)}{\pi} \right) + \frac{x \cos \theta_0}{\xi}$$
(3.14)

## 3.2.4 Evaluation of phase changes and displacement components

A deformation of the sample leads to a change in the speckle pattern entering the detector and therefore a change in the phase.

$$\Delta\phi_{\alpha}(x, y, f) = \phi_{\alpha, 2}(x, y, f) - \phi_{\alpha, 1}(x, y, f)$$
(3.15)

where subscripts 1 and 2 represent the sample states before and after deformation and  $\phi_{\alpha,i}(x, y, f)$  represents the phase at a peak centred at frequency *f* in the Fourier transform,  $\tilde{I}(x, y, f)$ .  $\Delta \phi_{\alpha}$  is therefore the phase change measured at point (x, y, f) with z given by Eqn. (3.7).  $\alpha$  denotes the azimuth of the incident illumination beam as shown in Fig. 3.4.



Figure 3.4. TSI illumination configuration.

By combining the real and imaginary components of the Fourier transform of the intensity signals obtained before and after the deformation the change in phase,  $\Delta \phi_{\alpha}(x, y, f)$ , Eqn. (3.15) can be written as:

$$\Delta\phi_{\alpha}(f) = \tan^{-1}\left\{\frac{\operatorname{Im}[\widetilde{I}_{\alpha,1}(f)]\operatorname{Re}[\widetilde{I}_{\alpha,2}(f)] - \operatorname{Im}[\widetilde{I}_{\alpha,2}(f)]\operatorname{Re}[\widetilde{I}_{\alpha,1}(f)]}{\operatorname{Re}[\widetilde{I}_{\alpha,1}(f)]\operatorname{Re}[\widetilde{I}_{\alpha,2}(f)] + \operatorname{Im}[\widetilde{I}_{\alpha,1}(f)]\operatorname{Im}[\widetilde{I}_{\alpha,2}(f)]}\right\}$$
(3.16)

where the dependence with (x, y) has been dropped for clarity.

When the sample is deformed and a point at coordinates (x, y, z) moves to a new position (x+u, y+v, z+w) then the change in phase is given by the dot product:

$$\Delta \phi_{\alpha} = \boldsymbol{K}_{\alpha} \cdot \Delta \boldsymbol{r} \tag{3.17}$$

where  $\Delta \mathbf{r} = (u, v, w)$  and  $\mathbf{K} = \mathbf{k}_i - \mathbf{k}_o$  is the sensitivity vector given by the difference between the illumination and observation wave vectors  $\mathbf{k}_i$  and  $\mathbf{k}_o$ , respectively.

In order to evaluate both in-plane (horizontal and vertical) and the out-of-plane displacement components, it is convenient to consider four illumination azimuth angles  $\alpha=0^{\circ}$ , 90°, 180° and 270°. Equation (3.17) can be expressed for each azimuth as:

$$\Delta\phi_0 = \frac{2\pi}{\lambda} n_0 \left[ u \sin \theta_C + w (1 + \cos \theta_C) \right]$$
(3.18)

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$$\Delta\phi_{90} = \frac{2\pi}{\lambda} n_0 \left[ v \sin\theta_C + w (1 + \cos\theta_C) \right]$$
(3.19)

$$\Delta \phi_{180} = \frac{2\pi}{\lambda} n_0 \left[ u \sin(-\theta_C) + w \left( 1 + \cos(-\theta_C) \right) \right]$$
(3.20)

$$\Delta\phi_{270} = \frac{2\pi}{\lambda} n_0 \left[ v \sin(-\theta_C) + w \left( 1 + \cos(-\theta_C) \right) \right]$$
(3.21)

In Equations (3.20) and (3.21) the central illumination angle is incident from the opposite lateral direction and is therefore negative. The in-plane, u and v, and out-of-plane, w, displacement components can be obtained by the changes in phase from two opposite lateral directions. Data acquired from a scan with the illumination from just one direction contains a combination of both in- and out-of-plane components; acquisitions from these pairs of azimuth angles enable the extraction of these separate components.

The in-plane change in phase is given by the difference of the phase changes in the azimuth angle pairs and is calculated in a similar way to Eqn. (3.16).

$$\Delta \phi_x = \Delta \phi_0 - \Delta \phi_{180} = \frac{4\pi}{\lambda} n_0 u \sin \theta_C$$
(3.22)

$$\Delta \phi_{y} = \Delta \phi_{90} - \Delta \phi_{270} = \frac{4\pi}{\lambda} n_{0} v \sin \theta_{C}$$
(3.23)

The addition of the phase changes provides the out-of-plane component. Two independent measurements for the out-of-plane phase change can be determined, and are given by Eqns. (3.24) and (3.25):

$$\Delta\phi_{\alpha}(f) = \tan^{-1}\left\{\frac{\operatorname{Im}[\widetilde{I}_{\alpha,1}(f)]\operatorname{Re}[\widetilde{I}_{\alpha,2}(f)] + \operatorname{Im}[\widetilde{I}_{\alpha,2}(f)]\operatorname{Re}[\widetilde{I}_{\alpha,1}(f)]}{\operatorname{Re}[\widetilde{I}_{\alpha,1}(f)]\operatorname{Re}[\widetilde{I}_{\alpha,2}(f)] - \operatorname{Im}[\widetilde{I}_{\alpha,1}(f)]\operatorname{Im}[\widetilde{I}_{\alpha,2}(f)]}\right\}$$
(3.24)

$$\Delta \phi_{z_x} = \Delta \phi_0 + \Delta \phi_{180} = \frac{4\pi}{\lambda} n_0 w (1 + \cos \theta_C)$$
(3.25)

$$\Delta\phi_{z_{y}} = \Delta\phi_{90} + \Delta\phi_{270} = \frac{4\pi}{\lambda} n_0 w (1 + \cos\theta_C)$$
(3.26)

Notice how Eqn. (3.24) is similar to Eqn. (3.16), but this time the signs of the terms in the {} brackets are reversed. Simple rearranging of the equations for the phase changes in each lateral component yields the sample displacement as follows:

$$u = \Delta \phi_x \frac{\lambda}{4\pi n_0 \sin \theta_C}$$
(3.27)

$$v = \Delta \phi_y \frac{\lambda}{4\pi n_0 \sin \theta_C}$$
(3.28)

$$w_x = \Delta \phi_{z_x} \frac{\lambda}{4\pi n_0 (1 + \cos \theta_C)}$$
(3.29)

$$w_{y} = \Delta \phi_{z_{y}} \frac{\lambda}{4\pi n_{0} (1 + \cos \theta_{C})}$$
(3.30)

The out-of-plane displacement can be calculated by finding the average between  $w_x$  and  $w_y$ .

## 3.3 Prototype TSI system

Figure 3.5 shows a diagram of the TSI prototype described in Ref. [6]. The light source was a continuous wave laser ( $\lambda = 532$ nm, 100mW). In-plane symmetric and collimated illumination beams were tilted continuously by means of a tilting mirror (TM) driven by a piezoelectric actuator controlled by a ramp generator (RG). Light scattered from the sample was imaged onto a CMOS photodetector array (C) with an 8-bit dynamic range. Reference and object beams were recombined with a wedge beam splitter (WBS) onto detector C to prevent spurious fringes at the detector from multiple reflections of the object beam within the thickness of the beam splitter. This was absolutely essential in order to avoid multiple peaks in the spectrum, which would appear in the reconstruction as several overlapped versions of the object. Separate optical fibres were used to launch object and reference beams. This configuration is very simple to set up, but movements in either fibre strains them, affecting the polarisation of the beams and thus the interference signal (modulation and DC term). The tilting mirror was positioned before a cube beam splitter CBS, meaning that both illumination beams can tilt equal and opposite amounts regardless of whether the left or right hand path is used to illuminate the sample. The distance *r* between the pivot axis of the tilting mirror (at

TM in Fig. 3.5) and the object leads to the beam travelling a distance  $\Delta s = r\Delta \theta$  across the object. As the beam's section is limited in size, points on the object would be illuminated only during a fraction of the full tilt scan. This limit to the effective tilting angle  $\Delta \theta$  translates into a limit to the depth resolution that can be achieved, as expressed by Eqn. (3.10).



Figure 3.5. Diagram of the prototype TSI system described in Ref. [6] showing optical fibres  $OF_1$  and  $OF_2$ ; tilting mirror TM; cube beam splitter CBS; wedge beam splitter WBS; reflecting mirrors M1 and M2; sample object O; reference surface R; ramp generator RG; camera detector array C; screen S; lenses  $L_1$ - $L_4$ .

## 3.4 Summary

The capabilities of tilt scanning interferometry make it an ideal technique for 3D depthresolved measurement of semi-transparent materials. Both in-plane and out-of-plane displacements have been previously measured using a prototype, which had a depth resolution of approximately 1mm and a depth range of around 10mm.

A description of the working principles of TSI was presented, explaining the procedure to reconstruct the sample. A sequence of speckle interferograms is recorded whilst continuously scanning through a range of tilt angles, creating depth-dependent Doppler shifts into the interference signal. Fourier analysis of the interference signal provides depth-resolved information about the internal microstructure of the sample. By repeating this scan at equal and opposite azimuths it is possible to obtain two three-dimensional phase change volumes. The sum of the two volumes produces the out-of-plane sensitive volume and the difference gives up the in-plane phase volume in one lateral direction.

A description of the first prototype TSI system was also presented, including a description of the components. It's main limitations were the lack of full sensitivity and a limited depth resolution due to the small tilting range of the illumination beam. Chapter 4 will expand on these limitations that inspired the development and design of a new full sensitivity TSI system before describing the new design itself, including 1) the optical setup, 2) control electronics, 3) synchronisation scheme, 4) data acquisition procedure (including a graphical user interface that was developed) and 5) data processing to reconstruct the object microstructure.

# Chapter 4

# Full sensitivity TSI system

# 4.1 Introduction

The first TSI system described in the previous chapter and in Ref. [6] was designed as a proof-of-principle experiment and as such is a prototype setup. The system was successful in proving the concept of TSI but several limitations became apparent, which Table 4.1 summarises along with the corresponding positive system attributes.

This chapter details a new TSI system designed and assembled in order to overcome those limitations and improve on the performance, most notably the depth resolution and sensitivity in all directions. The limitations of the prototype also concealed further problems that are inherent to the TSI method or data processing; notably the small tilting range of the illumination beam hid the fact that a chirp in the intensity signal is present and more pronounced over a large tilting range. The effect of the chirp is discussed in more detail in the Section 4.3.2.

Table 4.1. A list of attributes and limitations of the prototype TSI system and the corresponding limitations.

	Attributes	Limitations
1	Simple optical setup.	Distance of pivot point from object
		limits the size of the gauge volume.
2	Depth-resolved displacement measurements.	Small tilting range limits depth
		resolution to ~1.1mm.
3	In-plane and out-of-plane sensitivities	Only one in-plane displacement
	decoupled using left and right symmetric	component is measured.
	illumination directions.	
4	Tilting mirror is moved by a ramp generator-	Tilting mirror driver is not linear,
	controlled pzt actuator	which reduces depth resolution.
5	Pzt actuator is controlled by a ramp	Lack of tilt repeatability introduces
	generator.	spurious phase offset.
6	No moving parts except for the pzt driven	Only one in-plane displacement
	tilting stage.	component is measured.
7	8-bit camera detector.	Insufficient discretisation levels in
		the measured signal modulation (8-bit
		CMOS camera).
8	Field of view is 256×256 pixels.	Effective field of view: 7.2×7.2mm.
9	A reference plate is positioned in front of the	Requires a reference surface to
	sample.	compensate for errors in the data.

# 4.2 Full sensitivity TSI system

There are several differences between the new TSI system and the prototype described earlier or other similar systems (see angular spectrum scanning in Section 2.2.7) that aim to address the limitations described in Table 4.1. The prototype was designed to perform measurements from two opposing azimuths and was capable of determining one in-plane and out-of-plane measurements. However the in-plane sensitivity was only along one axis and therefore any

displacement component in the vertical direction (out of the plane of the diagram in Fig. 3.4) was missed. Another difference is the position of the pivot axis of the tilting illumination beam. The pivot axis in the prototype is located on the tilting mirror (see Fig. 3.4), itself located before the cube beam splitter CBS and reflecting mirrors  $M_1$  and  $M_2$ . With the pivot axis so far away from the sample, small tilts in the tilting mirror lead to large displacements of the illumination beam onto the sample: Too much of a tilt leads to the sample not being illuminated and therefore a smaller gauge volume is the result. Furthermore, the smaller tilting range resulting from this constraint leads to an inferior depth resolution as highlighted in Eqn. 3.9. To counter this limitation, the new system is designed to position the effective pivot axis as close to the sample as possible, allowing a larger tilting range and hence a larger gauge volume and an improvement on the depth resolution.

The interferometer was designed to place the pivot axis on the object surface to increase the size of the gauge volume. It uses collimated illumination, i.e. the illumination beam wavefront radius of curvature is very large, i.e. towards  $\infty$ . A schematic view of the new optical setup is shown in Fig. 4.1. A laser beam (Lightwave 142,  $\lambda = 532$ nm, 50mW) is launched into a polarisation-preserving optical fibre, OF. The input power on the fibre is controlled by a half-wave plate and a polarising beam splitter, HWP<sub>1</sub> and P<sub>1</sub>, respectively. Lens L<sub>1</sub> collimates the beam that exits OF while polariser P<sub>2</sub> attenuates residual orthogonal components that may have been induced in the optical fibre due to strain. The entire interferometer from the output end of OF onwards is mounted on a rotation stage so that the illumination beam can be rotated around the observation (*z*) axis to describe a cone, with the object placed at the apex of the cone (See Figs. 3.3 and 4.2).

## 4.2.1 Rotating stage

In order to address limitation 3 in Table 4.1, the interferometer was mounted on a rotation stage with a clear aperture. The illumination angle is rotated around the optical axis (*z*-axis), on which the camera is located. A schematic of the illumination is shown in Fig. 3.3. The illumination angle lies on the plane formed by the illumination direction and the *z*-axis. In order to obtain the in-plane displacement component along the *x*-axis, an image sequence for illumination directions with azimuth angles  $\alpha = 90^{\circ}$  and  $\alpha = 270^{\circ}$  are recorded. Azimuth

angles  $\alpha = 0^{\circ}$  and  $\alpha = 180^{\circ}$  are used for the in-plane component along the *y*-axis. The reference beam lies on the optical axis, which is parallel to the *z*-axis, enabling the interferometer to be sensitive to the out-of-plane displacement components. The rotating stage is a Newport URS150PP precision rotating stage in conjunction with a ESP300 3-axis motion driver, though only one axis is used in this case. It is capable of 360° motion and is accurate to  $0.03^{\circ}$  (524µrad) with  $0.002^{\circ}$  (34.9µrad) repeatability. The driver is controlled from a PC via a serial connection.

## 4.2.2 Tilting stage

The prototype TSI system had a small tilting range of 4.8mrad in the illumination beam, resulting in a depth resolution of around 1.1mm. Moreover, as the pivot axis of the tilting beam was far from the object, the beams moved sideways across it thus reducing the effective 'gauge' volume – Fig. 4.1(a). In the new setup, the object beam is steered towards the sample via a mirror mounted on a PZT driven closed-loop tilting stage (Physik Instrumente S-334-2SL) with high repeatability ( $\pm$ 5µrad), a tilting step as small as 5µrad and a tilting range of 50mrad (leading to a beam tilting range of 100mrad upon reflection). In order to maximise the effective 'gauge' volume, the beam's pivot axis needs to be as close as possible to the object – Fig. 4.1(b). The central illumination angle  $\theta_c$  was set to  $\pi/4$ , as it was the case in the first TSI prototype.



Figure 4.1. The size of the gauge volume is affected by the position of the pivot point of the tilting illumination beam.



Figure 4.2. Schematic of the second generation TSI interferometer showing: laser source LS; half wave plates HWP<sub>1</sub>, HWP<sub>2</sub>, HWP<sub>3</sub>; polarisers P<sub>1</sub>, P<sub>2</sub>, P<sub>3</sub>; optical fibre OF; mirrors M<sub>1</sub>; polarising cube beamsplitter PCBS; tilting mirror TM; object O; compensating plate CP; plate beamsplitter PBS, pinhole PH; aperture stop AS; camera detector array C and lenses L<sub>1</sub> to L<sub>8</sub>. The components within the dotted box are mounted on the breadboard, which rotates about the optical axis of the camera, see Section 3.2.4.

# 4.2.3 Optical setup

## 4.2.3.1 Single optical fibre

As shown in Fig. 4.2, a single optical fibre is used in the new TSI system due to the available laser being impossible to mount on the rotating stage. The fibre is a polarisation-preserving fibre. However, movement or twists in the fibre caused by the rotation of the interferometer still creates small strains in the optical fibre, changing the optical path length for non-equal polarisation components. This in turn changes the phase of the beam affecting polarisation components in the beam going through it, i.e. a perfectly polarised beam entering the fibre
will exit the fibre elliptically polarised. This change in polarisation affects the intensity of the output beam. The prototype system used two separate fibres but the system was stationary and the fibres never moved and so no orthogonal components were introduced. If two fibres were used in the new system, differing amounts of orthogonal components would be introduced in the separate fibres, varying the intensity of the exiting beams and hence varying the reference beam and object beam intensities, affecting the detected signal modulation and preventing the extraction of depth resolved information which is encoded in the modulation.

## 4.2.3.2 Conditioning optics

The breadboard, a mounting plate that houses most optical components, can be divided up into three main sections. The first section contains the components between the output of optical fibre OF, up to and including the polarising cube beamsplitter, PCBS; the second section is the reference beam and the optical components involved, including the plate beamsplitter, PBS, and lenses  $L_6$  and  $L_7$ ; the third section is the object beam and the optical components involved, including the tilting mirror, TM, and lenses  $L_2$  to  $L_5$ . The camera and lens  $L_8$  do not lie on the breadboard but are mounted in a fixed position relative to the rotating breadboard on the optical axis. The second and third sections of the breadboard will be discussed in the next sections.

Upon exiting OF, the beam is collimated by lens  $L_1$  and polariser  $P_2$  attenuates any residual orthogonal components that may have been induced in the optical fibre due to strain. A polarising cube beamsplitter, PCBS, is used to split the beam into illumination and reference beams while a second half wave plate, HWP<sub>2</sub>, is used to control their intensity ratio. PCBS has an extinction ratio of 100:1.

## 4.2.3.3 Reference beam

A ray diagram showing the optical components within the reference beam path can be seen in Fig. 4.3 below. The reference beam is focused by lens  $L_6$  and spatially filtered with a pin hole, PH. The latter is then imaged by lens  $L_7$  onto the aperture stop of the imaging lens  $L_8$ ,

AS, so that a smooth Gaussian profile is obtained at the CCD detector array, C. Polariser  $P_3$  ensures that light scattered from the object and the reference beam have the same polarisation to maximise the interference signal modulation.



Figure 4.3. The reference beam as it recombines with the light scattered from the sample.



Figure 4.4. Ray paths in the object beam directed onto the sample via the tilting mirror and a magnifier formed by lenses  $L_2$  to  $L_5$ .

Half wave plate HWP<sub>3</sub> can be adjusted to balance the reference and object beams at the camera detector. Lens  $L_6$  is an Olympus 4× microscope objective 0.10 NA with a working distance of 18.5mm. The focal length of  $L_7$  is 120mm and  $L_8$  is a telecentric lens, with a focal length set to 60mm and NA set to 0.19.

Light scattered from the sample is recombined with the reference beam at the plate beamsplitter plate, PBS. A transparent optical window, CP, of equal thickness and refractive index as the beamsplitter is used as a compensator plate, but positioned orthogonally to it. This prevents motion of the image due to refraction in the plate beamsplitter while it rotates about the optical axis.

## 4.2.3.4 Object beam

In order to maximise the effective 'gauge' volume in the new setup, the pivot axis of the object beam needs to be as close as possible to the sample surface. This was achieved by imaging the tilting mirror onto the object by using a 4f system (plano-convex lenses  $L_2$  and  $L_3$ ) and a 4× expander (plano-convex lenses  $L_4$  and  $L_5$ ) as shown in Fig. 4.4. The central illumination angle  $\theta_C$  was set to  $\pi/4$  to the observation direction.

In this 4f system the focal lengths of  $L_2$  and  $L_3$  are equal.  $L_2$  focuses the collimated beam to a point at plane A as seen in Fig. 4.5.  $L_3$  collimates the diverging beam. The tilting mirror is imaged at plane B, effectively bringing the mirror closer to the sample object. In the current setup, the focal lengths of  $L_2$  and  $L_3$  are 25mm.

The ratio of the focal lengths of lenses  $L_4$  and  $L_5$  determine the magnification of the beam. With  $f_4$  being 25mm and  $f_5$  being 100mm, this gives a magnification of 4. There is a compromise in the magnification of the expander between the beam diameter and the beam tilting range. The beam diameter at the tilting mirror and after the 4f system is 7mm which  $L_4$ and  $L_5$  magnify by 4 to a diameter of 28mm. This 28mm diameter is collimated and imaged onto the sample at point D.



Figure 4.5. The illumination beam path consists of a 4f system and a beam expander.  $f_0 = f_4 = 25$ mm,  $f_5 = 100$ mm.

The tilting range of the beam reflected off TM is 100 mrad (-50 to +50 mrad), is thus reduced to 25 mrad (-12.5 to +12.5 mrad) at the object. This trade-off is of course dependent on the object size and the required depth resolution which ultimately defines a required magnification, as the size of TM is fixed.

#### 4.2.4 Graphical user interface (GUI)

A GUI was developed in Matlab® to facilitate the operation of the system. A screenshot of the GUI and its features are shown in Fig. 4.6.

The user is required to enter input parameters for the illumination, sample and camera. The illumination and sample parameters are not essential but are required for the calculation of the system performance and do not affect the hardware controls; more specifically the depth range, the depth resolution and the sensitivity. *"Illumination parameters"* include the light wavelength and centre illumination angle,  $\theta_C$ . The magnification of the object beam and the window function used for calculating the system depth resolution are also required. *"Sample parameters"* include the refractive indexes of the object under study and that of the surrounding medium. *"Camera parameters"* specify the CCD detector size and location and size of the region of interest on the acquired image which will appear in the display. An additional input camera parameter is the *"Azimuth offset"* which describes the angle at which

the rotation stage needs to be set at in order for the illumination beam azimuth to be aligned with the azimuth of the sample. The "*Tilting mirror position*" cell sets the upper and lower tilt angles and the step interval. The "*Manual positioning*" buttons can be used to manually rotate the interferometer to preset azimuths which are parallel to the *x*- and *y*-axes. The "*Run*" button starts the entire acquisition sequence. "*Run once*" is used when just one acquisition is needed at the current azimuth and sample state only, as opposed to all other azimuths and sample states. "*Get snapshot*" triggers the camera to acquire a single image and is used during image adjustment and preparation.

Another parameter that give additional control to the user include the "*Number of illumination directions*" for when running a full acquisition sequence. The sample can be measured along just one axis (x), or two (x and y). Furthermore, the user can specify whether the sample will be deformed between acquisitions, determining the number of acquisition sequences to perform.



Figure 4.6. Snapshot of the graphical user interface used to control the TSI system.

# 4.3 Data acquisition and data processing

Figure 4.7 is an extension of Fig. 3.2 and shows a diagram that includes the main stages of data processing from the data acquisition to the reconstruction of the sample microstructure and displacement measurement.



Figure 4.7. Flow chart of the TSI procedure for sample microstructure reconstruction.

### 4.3.1 Acquisition of interferograms

Image acquisition is controlled by a personal computer (PC) that synchronises the rotating stage, the mirror tilting driver and the camera. The rotating stage is set to the correct azimuth and the mirror is tilted with a step  $\delta\theta_0$  between consecutive images in the range  $-\frac{\theta_0}{2}$  to

 $+\frac{\theta_0}{2}$ . The camera used for the image acquisitions is a VDS Vosskühler CCD 1300 QLN with a 12-bit digital output and is able to record up to 12.5 images per second. The detector array contains 1280 × 1024 square pixels, each measuring 6.45µm × 6.45µm The exposure time was set to 20ms using a telecentric lens with a numerical aperture NA=0.19.

## 4.3.2 DC term subtraction and complex demodulation

Figure 4.8 shows the interference intensity signal for an arbitrary pixel on the reference surface throughout the scan. This reference surface consists of a flat aluminium plate located where the surface of the object will lie. It is apparent that the frequency decreases throughout the chirp. The instantaneous phase corresponding to this signal was obtained by: 1) removing the instantaneous DC component of the intensity signal in Fig. 4.8 by subtracting a smoothed version of itself, obtained by a low frequency spline fitting; 2) multiplying the signal by a Hann window; 3) evaluating the Fourier transform of the DC-free intensity; 4) removing the negative side of the frequency spectrum; 5) computing the inverse Fourier Transform [5] to obtain a complex analytical signal and 6) unwrapping the phase. The analytical signal can be described as

$$C(\theta_0) = A e^{i\phi} \tag{4.1}$$

The unwrapped phase,  $\phi$ , of the analytical signal thus obtained is shown in Fig. 4.9. It has a smooth quadratic behaviour during most of the scan, which is responsible for a wide spectral peak obtained through the Fourier transform of the intensity signal seen in Fig. 4.8. It can be described in terms of the illumination angle as

$$\phi = a\theta_0^2 + b\theta_0 + c \tag{4.2}$$

The quadratic term,  $a\theta_0^2$  that produces a frequency chirp, can be removed by multiplying the analytical signal described in Eqn (4.1) by  $\exp(-ia\theta_0^2)$ , a process known as complex demodulation.

The remaining demodulated signal can be expressed as

$$\tilde{I}_{\text{demod}}\left(x, y, f(\theta_0)\right) = A e^{i(b\theta_0 + c)}$$

$$\tag{4.3}$$



Figure 4.8. Intensity distribution at a particular pixel as the tilting angle is scanned through the tilting range.



Figure 4.9. Unwrapped phase of the pixel intensity distribution.



Figure 4.10. Peak width profile of the cross-section of the aluminium plate before complex demodulation.



Figure 4.11. Cross-section of the aluminium plate, averaged along the *y*-axis, before complex demodulation.

Figure 4.11 shows the reconstruction of the cross section of the reference surface in the *xz* plane averaged along the *y*-axis. What should appear as a sharp line appears as a broad band, which indicates all the values that the instantaneous frequency has taken during the tilt scan.

The Fourier transform, from Eqn. (3.6), of the demodulated complex signal is finally computed for all pixels (m, n) to reconstruct the full data volume (x, y, z) with the sample surface and/or internal microstructure. The results of the complex demodulation process are displayed in Figs. 4.12 and 4.13, which show the modulus of the Fourier transforms of the intensity signal for an *xz* cross-section of the data volume, and at one pixel, respectively. The bright white tilted line in Fig. 4.12 and the large peak in Fig. 4.13 represent the opaque surface of the reference sample and correspond to the second term on the right hand side of Eqn. (3.6). The DC peak is removed during the complex demodulation process and therefore does not appear in the figures. The autocorrelation term is shown as the low frequency noise closer to 0. The modulus of the Fourier transform has been averaged along the *y*-axis to

reduce the speckle noise. The width of the peak in Fig. 4.13 represents the depth resolution of the system, described by Eqn. (3.10).

Complex demodulation is just one method that can be used to remove the chirp from the intensity signal, and it was the method successfully employed in this full sensitivity TSI system. Another approach would be to examine the unwrapped phase of the intensity distribution, such as that shown in Fig. 4.9, by interpolating the nonlinear tilt steps corresponding to a constant linear phase change and then applying the new tilt steps at the data acquisition stage. This is equivalent to the strategy followed by Duan et al in angular spectrum scanning [108], so to obtain constant movements of the height components of the k-vector. In this case, the chirp will be absent from the intensity signal and the data processing can proceed straight to the reregistration stage. The advantage of this approach is that the complex demodulation stage is bypassed, thus reducing the time spent demodulating the chirped intensity signal. The drawback, however, is that the tilting steps of the illuminations beam will need to be programmed into the tilting stage before every acquisition sequence, and the tilt steps pre-calibrated before each set of acquisitions.



Figure 4.12. Cross-section of the aluminium plate after complex demodulation and before reregistration. The intensity is averaged along the *y*-axis.



Figure 4.13. Peak width profile of the cross-section of the aluminium plate after complex demodulation.

Figure 4.13 shows the profile of the reference surface after chirp removal and averaging all *yz* cross sections. The effective depth resolution obtained, expressed as a full width half maximum (FWHM) value, was 122µm whereas the value obtained from Eqn. 3.9 (this time the full width measured at the first zero crossing points) is 120µm, using  $\theta_c = \pi/4$ rad,  $\Delta \theta_0 = 25$ mrad,  $\lambda = 532$ nm,  $n_0 = n_1 = 1$  and a Hann windowing function, i.e.  $\gamma = 4$ .

## 4.3.3 Re-registration

As seen in Fig. 4.12, the sample surface, which lies perpendicular to the optical axis of the camera, appears tilted in the reconstructed space after chirp removal. This is because of the oblique illumination, as expressed in the *x*-dependent term in Eqn. 3.3. This term needs to be removed in order to reconstruct the surface / internal structure of the sample without any geometric distortions. One way to do it is to find the coefficients of the plane  $z = a_1x + a_2y + a_3$  that fits the sample surface as detected after demodulation and then to subtract the *x*-dependent component  $a_1x$  from all coordinate points in the (x, y, z) data volume. Fig. 4.14

shows the sample surface after this correction was made to Fig. 4.12. and it represents a cross section of the opaque reference surface without the tilt introduced by the oblique illumination.



Figure 4.14. The reconstruction of the cross-section of an aluminium plate after demodulation and re-registration. The figure shows the average intensity along the *y*-axis.

## 4.4 Summary

With only two possible illumination directions, the first TSI prototype was capable of determining in-plane displacement only along one lateral direction. By modifying the existing concept of TSI, full sensitivity 3D whole-field measurements become possible. A relocation of the tilting mirror after the beamsplitter and closer to the sample allows for a larger gauge volume and a wider tilting range and thus an improvement on the depth resolution.

By using a flat, optically 'rough', aluminium plate, the signal obtained from an acquisition sequence demonstrated that a chirp is present in the intensity distribution. This chirp has been found to be quadratic in nature and broadens the peaks in the Fourier transform. Complex demodulation was used to remove the chirp and therefore narrow the spectral peak. The depth

resolution of the system was validated and was a significant improvement over the prototype ( $\sim 120 \mu m \text{ vs.} \sim 1.1 mm$ ).

Without the process of re-registration, the reconstruction of the sample appears tilted which will in turn distort any sub-surface microstructure. Re-registration essentially eliminates the lateral tilt that distorts the geometrical representation of the sample. This step is also essential for a different purpose: in phase-measurement applications with multiple illumination directions (different central angle) the re-registered data volumes can be combined in a common coordinate system to evaluate multiple sensitivities.

When reconstructing the object from the intensity data, certain assumptions were made: The refractive index throughout the object and also that of the surrounding medium are constants. The quadratic coefficient, a, removed during complex demodulation is the average over the whole ROI and its value is used for all pixels, see Section 5.4.1. The reference opaque surface is assumed to be flat.

Chapter 5 investigates the performance of the TSI system including 1) the stability of the beam intensity, 2) the repeatability of the rotating stage and tilting mirror, 3) a look at speckle decorrelation, 4) the effects of beam divergence and the position of the illumination beam pivot point and 5) optical aberrations.

# Chapter 5

# Evaluation of the system performance

# **5.1 Introduction**

This chapter will examine various aspects of the new proposed TSI system and their impact on the performance of the system, including: 1) illumination beam stability; 2) repeatability of the rotating stage; 3) optimisation of the quadratic coefficient used for complex demodulation and chirp removal; 4) speckle decorrelation; 5) position of the pivot axis; and 6) curvature and optical aberrations of the illumination beam. Potential and existing problems are identified and investigated and possible solutions are presented if applicable.

## 5.2 Beam intensity stability

As the setup needs to rotate to different azimuth angles during a full sensitivity measurement, the optical fibre moves with it since the laser is not mounted on the rotating stage. Despite being polarisation-preserving fibres the intensity of the output beam can modulate due to fibre strain. Figures 5.1 and 5.2 highlight the importance of polariser P<sub>2</sub> in Fig. 4.2, at the exit of the optical fibre. In order to measure spurious variations in beam intensity, rather than the modulation caused by the interference pattern between the reference and scattered light from the object, the reference beam was blocked and an image acquisition sequence was run at one azimuth  $\alpha = 0^{\circ}$ . A flat, opaque surface was used as sample. During the acquisition the fibre was tapped continuously and the variations in intensity of the beam were observed.

When polariser  $P_2$  is not in place, the intensity variations are fairly large, with a standard deviation of 99 and intensity range, defined as  $I_{max} - I_{min}$ , of 615 grey levels, as seen in Fig. 5.1 (the DC is removed); the detector is a 12-bit camera giving 4096 grey levels. This indicates the presence of an orthogonal component in the beam at the fibre output, caused by stresses in the optical fibre as it moves.

Figure 5.2 demonstrates the effect the polariser has on the beam at the fibre output. With the polariser in place the intensity signal shows much more stability, with a standard deviation of 4 and range of 27 grey levels. A significant portion of the fluctuating orthogonal components have been blocked and thus prevented from contributing to the detected intensity signal. This ensures that the intensity variations observed when running an image acquisition sequence on an actual sample is due to the sample itself and the interference between the reference beam and the light scattered back from the sample, and not due to fibre birefringence effects.



Figure 5.1. Mean frame intensity with the DC term removed without the use of polariser  $P_2$  while the optical fibre is continually tapped.



Figure 5.2. Mean frame intensity with the DC removed and polariser  $P_2$  in position as shown in Fig. 4.2.

## **5.3 Experimental repeatability**

#### **5.3.1 Rotation repeatability**

The rotation repeatability is a measure of the precision of the rotating stage and is an essential parameter to know. Interferometry is very sensitive to displacements and small errors in the rotation stage position can add to errors in the in-plane components of the measured displacements. Those in turn introduce spurious compressive strains. When performing the three-dimensional sensitivity measurements, data acquisitions are taken from multiple azimuths before and after any sample deformations. It is therefore essential to the whole measurement process to know the level of repeatability of the rotation stage.

For a given azimuth of the illumination beam, e.g.  $\alpha = 0^{\circ}$ , the phase change due to a relative rotation around the *z*-axis between the illumination arm and the sample is given by

$$\Delta \phi_{\alpha} = \frac{2\pi n_0}{\lambda} \left[ u \sin \theta_C + w (1 + \cos \theta_C) \right]$$
(5.1)

where *u* represents the in-plane component of the displacement, *w* represents the out-of-plane component and  $\theta_{\rm C}$  is a fixed central illumination angle. Using the parameters of the 3D full sensitivity TSI system mentioned in Section 4.2,  $\lambda = 532$ nm,  $\theta_{\rm C} = \pi/4$  rad and  $n_0 = 1$ . *w* can be disregarded since the rotation stage only provides in-plane displacement. For the full sensitivity TSI system Eqn. (5.1) gives an in-plane displacement of 0.752µm per fringe, equivalent to a rotation of 62.7µrad over the FOV. The change in phase due to rotation was determined by first performing an acquisition at each azimuth, rotating the stage back to the start and then performing another acquisition at each azimuth. The phase difference between each acquisition was calculated and the results shown in Fig. 5.3. Each azimuth displays a constant phase difference of less than 1 fringe, inferring that there is a repositioning error of less than 62.7µrad due to the rotation stage. The 'stripe' that can be seen clearly parallel to the fringe direction is due to the position of the pivot point creating negative frequencies to appear on the Fourier transform.



Figure 5.3. The phase difference at each azimuth during rotation repeatability acquisitions at (a)  $\alpha = 0^{\circ}$ , (b)  $\alpha = 90^{\circ}$ , (c)  $\alpha = 180^{\circ}$  and (d)  $\alpha = 270^{\circ}$ .

## 5.3.2 Tilting stage repeatability

A similar evaluation was carried out to check the repeatability of the initial position of the tilting mirror. This was done by performing two acquisitions with a static sample and finding the phase difference between them, before repeating the process at the other azimuths. Eqn. (5.1) yields an out-of-plane displacement of  $0.312\mu$ m per fringe, since *u* is equal to 0 as there is no in-plane rotation. It can be seen in Fig. 5.4 that the phase difference is very small: ~ 0.5rad, which is equivalent to ~25nm out-of-plane displacement. Once again the 'stripe' is visible parallel to the fringe direction due to the pivot point. The slight tilt in the figures is due to a camera misalignment with the tilting axis.



Figure 5.4. The phase difference between tilting stage repeatability acquisitions at azimuths of (a)  $\alpha = 0^{\circ}$ , (b)  $\alpha = 90^{\circ}$ , (c)  $\alpha = 180^{\circ}$  and (d)  $\alpha = 270^{\circ}$ .

# **5.4 Depth resolution**

The depth resolution is defined as the minimum distance between layers inside the object measuring volume whose corresponding peaks in the frequency domain can be fully resolved. It was defined in Eqn. 3.9 in terms of the illuminating wavelength, the refractive parameter  $\xi$ , and also the tilting range  $\Delta \theta_0$ , the surrounding medium's refractive index  $n_0$  and a factor  $\gamma$ , that depends on the window function used during the evaluation of the Fourier transform of the intensity signal. In this section the influence of several factors affecting the depth resolution are studied and solutions are proposed to reduce their impact.

### 5.4.1 Optimising the quadratic coefficient for complex demodulation

The quadratic coefficient, *a*, that describes the phase of the intensity signal is given in Eqn. (4.2) and is position dependent. This coefficient was evaluated from the unwrapped phase for each pixel by polynomial fitting. The initial estimated value for *a* is taken from the average of the pixel coefficients over the whole image due to the spatial variation of this parameter caused by differences in the intensity modulation. Before any acquisition on a sample volume is carried out, an opaque reference surface is measured in order to find the optimum *a* value. This is done by examining the plot seen in Fig. 5.5 which shows a comparison of how the value of *a* changes the thickness of a reconstructed flat aluminium reference surface. If the value of *a* corresponding to the opaque reference surface is inaccurate then the peak in the demodulated Fourier transform will broaden, i.e. the reconstructed surface will appear as if it had depth. Therefore it is essential to determine an optimum value – the narrowest peak width in the plot. Since the sample is opaque the light cannot penetrate and the sample effectively has no depth. The expected reconstruction in the Fourier transform is that of a narrow peak representing the surface. The optimum *a* value for a reference surface yields the narrowest peak width and this can be clearly determined from Fig. 5.5 with *a* = -6.7×10<sup>-5</sup>.

A single *a* value is used to represent the phase over the whole field in the complex demodulation process, as opposed to determining its value for every pixel. The reason for this can be explained by the fact that the intensity modulation for some pixels can be irregular, yielding anomalous quadratic values. These anomalies would thus affect any pixel-wise demodulation. *a* is dependent on  $\delta\theta_0$ , due to the frequency of the change in the pixel intensities, therefore different values of *a* are calculated when tilting the illumination beam with differing intervals between successive frames.



Figure 5.5. The effect of different values of the quadratic terms on the performance of complex demodulation.

## 5.4.2 Speckle decorrelation

When an optically rough surface or a semi-transparent scattering material is illuminated with coherent light, the random superposition of light coming from all the illuminated scattering centres gives rise to a 3D speckle field around the object. This is known as objective speckle [14]. Part of this field enters the aperture of the imaging system and gives rise to a speckle pattern on the detector plane of the camera. If the illumination angle is tilted, keeping the observation direction and the sample fixed, the 3D speckle pattern rotates in space and thus moves across the imaging aperture. This leads to speckle decorrelation, which in speckle interferometry constitutes a limit to the maximum displacement/rotation of the sample. From an interferogram point of view, the fringe pattern obtained due to the deformation in a digital speckle pattern interferometry (DSPI) system, presents more and more fringes as the deformation increases. When the fringes cannot be resolved by the imaging system, only a

speckle pattern is observed. At this point the speckle before and after deformation is said to be decorrelated.

In TSI, this happens continuously as the illumination beam is tilted; the 3D speckle field moves across the imaging lens. Eventually, the speckle field at the beginning of the tilt scan may not bear resemblance with the speckle field further down the scan, at which point the interference intensity signal for a fixed point on the object (consider an opaque surface here for simplicity) will lose phase correlation.

In order to check the level of decorrelation in the TSI system, the following experiment was performed to assess the amount of movement of the objective speckle across the imaging aperture: an opaque (sandblasted aluminium) flat sample was illuminated through a full tilt scan around a central angle  $\theta_c$ . The imaging lens was removed from the camera in order to track the displacement of the 3-D speckle field as a function of tilting angle. In this way, a sequence of images was recorded of the speckle field, which as expected, moved across the detector array as the tilt scan progressed. Then one column of pixels at the centre of the image (aligned with the direction of motion of the speckles) was extracted from each frame in the sequence and a second image created by arranging the centre column in the first frame as the first column in the synthetic image, the centre column in the second frame as the second column of the synthetic image, and so on. In this way the synthetic image shown in Fig 5.6 was obtained. It displays tilting angle relative to  $\theta_c$  in the horizontal axis and position across the detector array along the vertical axis. The tilted lines are the speckles crossing the centre row of the detector as the illumination beam is scanned.



Figure 5.6. Movement of the objective speckle field over the CCD detector during a tilt scan.

Each pixel on the camera detector is  $6.45 \times 6.45 \mu m$  and using a region of interest of  $256 \times 256$  pixels, the size of the detector being used is  $1.65 \times 1.65 mm$ . The step interval between tilt positions of the mirror and also between frames in the acquisition is 0.02mrad. For one particular speckle, it enters the field of view at a point 4.45mrad on the frame number axis and leaves the field of view at a point 9.07mrad, corresponding to  $\Delta \theta_{\text{mirror}} = 4.62 mrad$  (which corresponds to the base of the triangle shown in dashed lines in Fig. 5.6).

The ratio  $\rho$  of speckle displacement to the diameter of the imaging lens, as measured at the aperture plane of the imaging lens, is a parameter closely related to speckle decorrelation. In the TSI system described in Chapter 4, with an aperture diameter of 34mm and a speckle displacement of 9.07mm for the full tilting range, this ratio is  $\rho = 0.27$ . This is much less than complete decorrelation ( $\rho = 1$ ), but still significant and may reduce depth resolution. It has

been shown that a decorrelation ratio  $\rho = 0.27$  leads to a phase standard deviation of around 0.9rad [117].

For the purposes of anticipating the speckle angular displacement as a function of illumination angle tilt, a simple model of the scattering surface can be used, by considering it as a diffraction grating, the equation for which is

$$\sin \beta_m = \sin \theta_0 + m\lambda F \tag{5.2}$$

where  $\beta_m$  is the diffraction angle of the *m*-th diffracted order,  $\theta_0$  is the angle of incidence relative to the normal of the plane of the grating,  $\lambda$  is the wavelength of light and *F* is the frequency of the grating (in lines per unit length). For  $\theta_0 = 45^\circ$ , m = -1 and  $\beta_m = 0^\circ$ , which corresponds to the -1 diffraction order travelling perpendicular to the grating (which corresponds to the observation direction in the TSI system – see Fig. 5.7), Eqn. (5.2) leads to  $\lambda F = 1/\sqrt{2}$ .



Figure 5.7. Ray diagram of a diffraction grating.

From Equation (5.2), small changes in  $\beta$ ,  $\Delta\beta$ , with respect to  $\theta_0$ , can be calculated from

$$\frac{d\beta_{-1}}{d\theta_0} = \frac{d}{d\theta_0} \left[ \sin^{-1} (\sin \theta_0 - \lambda F) \right]$$
(5.3)

For  $\lambda F = 1/\sqrt{2}$ , solving Equation (5.3) gives the following relationship

$$d\beta = \frac{1}{\sqrt{2}}d\theta_0 \tag{5.4}$$

Using the imaging system dimensions shown in Fig. 5.8, it can be shown that the maximum change in  $\beta$ ,  $\Delta\beta$ , is 79mrad.

The diffraction grating model enables the anticipation of the translation of the speckle field in front of the imaging lens. Using these dimensions of the detector and the distance from the object as shown in Fig. 5.9, the maximum change in the scattered angle  $\beta$ , is d $\beta$  = 3.2mrad.



Figure 5.8. Aperture and stand-off distance of the imaging system.



Figure 5.9. Detector array dimensions and stand-off distance.

Converting the tilt of the mirror before the speckles decorrelate, as measured from Fig. 5.6, to the tilt of the object beam

$$\Delta \theta_{beam} = \frac{reflection \times \Delta \theta_{mirror}}{magnification}$$
(5.5)

where the magnification = 4 and reflection = 2. For  $\Delta \theta_{\text{mirror}} = 4.62 \text{mrad}$ , Eqn (5.5) equates to  $\Delta \theta_{\text{beam}} = 2.31 \text{mrad}$ .

The ratio of the value of  $d\beta = 3.2$ mrad (from Fig. 5.9) and  $d\theta = 2.31$ mrad (from Fig. 5.6) is 0.72. Comparing the measured ratio of 0.72 to the theoretical value of  $1/\sqrt{2}$ , a 1.8% error is calculated, indicating that the measured experimental value is very close to the expected value from this diffraction grating model.

For the previously calculated value of  $\Delta\beta$  = 79mrad, from Eqn. (5.4) the maximum tilt for the illumination beam range before the speckles fully decorrelate is given as  $\Delta\theta_{0max} = 112mrad$ .

Due to the maximum tilt of the tilting mirror and the magnifying lenses, however, the maximum tilt of the illumination beam is 25mrad and from Eqn. (5.4) the maximum possible change in  $\beta$ ,  $\Delta\beta$ , is 17.7mrad. These values are lower than those required for the speckles to fully decorrelate so this is not likely to substantially degrade the depth resolution

## 5.4.3 Beam divergence and pivot axis position

In Section 3.2.1 and Ref. [6] it was assumed that the illumination beam was collimated, i.e. plane wavefronts were used. This simplifies the derivation of the main equations linking the position-encoding frequencies in the interference signal for each pixel. However it may be desirable to increase the size of the illuminated area without using optical components to collimate and/or tilt the beam whilst maintaining a large tilting range. Figure 5.10 shows the use a divergent beam whose centre of curvature, C, rotates about a pivot axis that is perpendicular to xz plane and intersects it at point A. The origin of the coordinate system is located at O, near which the object is placed.

It is regarded that the object as consisting of either an opaque surface (in the case of profilometry applications), or small particles sitting still in a medium of constant refractive index. Refraction effects at an interface are neglected. This simplification is worth considering in order to gain insight on the effect of both pivot axis location and wavefront radius of curvature on the frequency modulation in the interference signal. As the illumination beam is tilted about the pivot axis, the phase change at each point within the measurement volume (or gauge volume) is evaluated. The phase at the centre of curvature is assumed to remain constant, as would be the case in an interferometer where a mirror is used to steer a divergent beam. Point C thus behaves as a moving point source. As the illumination beam tilts throughout the scan, the centre of curvature describes an arc of radius AC. At different points on the object, the wavefront will experience a phase change as it moves while the beam is tilted. It can be seen in Fig. 5.10 that the incident wavefront moves relative to a point (x, y, z) as the beam pivots about point A and the centre of curvature moves from the initial to the final positions  $C[\theta_0(-\Delta\theta_0/2\delta\theta_0)]$  to  $C[\theta_0(\Delta\theta_0/2\delta\theta_0)]$ , respectively (C<sub>1</sub> and C<sub>3</sub> in Fig. 5.10). The distance d from the centre of curvature to point (x, y, z) therefore changes during the scan and can be expressed as

$$d(x, y, z, \theta_0) = \sqrt{[C_x(\theta_0) - x]^2 + [C_y(\theta_0) - y]^2 + [C_z(\theta_0) - z]^2}$$
(5.6)

where  $C_x(\theta_0)$ ,  $C_y(\theta_0)$  and  $C_z(\theta_0)$  are the Cartesian coordinates of the centre of curvature as a function of the illumination angle  $\theta_0(t)$  as defined in Eqn. (3.2). Equation (5.6) leads to a phase

$$\phi(x, y, z, \theta_0) = \frac{2\pi}{\lambda} n_0 d(x, y, z, \theta_0)$$
(5.7)

It can be shown that for the tilt angles considered here,  $\phi$  is well approximated by a second order polynomial in  $t\partial\theta_0$ , i.e.  $\phi(x, y, z, t) = a(t\partial\theta_0)^2 + bt\partial\theta_0 + c$ , with *a*, *b* and *c* parameters that are, in general, position dependent. The modulation frequency of the intensity signal for point (x, y, z) is, upon recombination with the reference beam (in units of cycles per frame):

$$f(x, y, z, t) = \frac{1}{2\pi} \frac{\partial \phi}{\partial t} = \frac{a \,\delta \theta_0^2}{\pi} t + \frac{b \,\delta \theta_0}{2\pi}$$
(5.8)

The first term in the RHS of Eqn. (5.8) corresponds to a time-dependent frequency shift,  $f_{\text{shift}}$ , that changes linearly with the tilting angle and the second term to a constant 'carrier' frequency  $f_{\text{carrier}}$ .

A numerical simulation was implemented to explore the effect of the beam curvature and the position of the pivot point by using the OA/R ratio, with OA the distance from the origin to the pivot point and R the distance from the origin to the centre of curvature of the beam. In the simulation, *d* and  $\phi$  are calculated for points around the origin within a 5 × 5 × 5mm cube using Eqns. (5.6) and (5.7). The phase is approximated with a second order polynomial that fits it with a rms error better than  $3 \times 10^{-5}$  rad. The intensity of the interference signal is computed as  $I=\cos(\phi)$ , which is Fourier transformed to obtain the frequency content of the signal.

Figure 5.11 shows  $\phi$ ,  $I(\theta_0 - \theta_C)$  and f for point (0, 0.005, -0.005) m in object space, a radius of curvature R=0.5m and the pivot axis 0.05m from the centre of curvature, i.e. OA/R=0.9. The predominantly quadratic phase behaviour and the frequency chirp are clearly seen, which leads to a broad frequency peak. Figure 5.12 shows contour plots on the xz-plane for  $f_{\text{carrier}}$  (a) and the maximum variation in  $f_{\text{shift}}$  throughout the scan,  $\Delta f_{\text{shift}}$ , (b).



Figure 5.10. As the centre of curvature of a divergent illumination beam moves from  $C_1$  to  $C_3$  the phase at point B in the sample changes proportionally to the distance between point B and the centre of curvature.



Figure 5.11. Signal corresponding to a point at (0, 5, 5) mm in the object space in Fig. 5.10 as the illumination angle is tilted from -12.5mrad to 12.5mrad around  $\theta_C = \pi/4$ : (a) Unwrapped phase change; (b) intensity; and (c) the magnitude of the Fourier transform of the intensity.

Notice that the carrier frequency in Fig. 5.12(a) is zero along the illumination direction (the field shown corresponds to the region around the origin in Fig. 5.10. It is positive above it and negative below it, as the wavefront moves towards or away from the object, respectively, as the illumination angle increases. The variation of the frequency shift  $f_{\text{shift}}$ , throughout the full tilting range  $\Delta \theta_0$  has the effect of broadening the narrow peak that would otherwise be detected in the Fourier transform of the interference signal had the frequency remained constant throughout the scan. The peak broadening  $\Delta f_{\text{shift}}$  is easily found by computing the difference between the maximum and minimum of  $f_{\text{shift}}$  during the scan. Fig. 5.12(b) shows that the peak width increases linearly *along* the illumination direction and remains nearly constant perpendicular to it. This variation is however very small across the field of view. For an opaque surface, this peak width will not change along the x axis. These figures suggest that along the central illumination direction there is no carrier frequency and therefore points along it within the object or at its surface will be modulated with such a low frequency that it will be impossible to separate the signal from the DC term and the autocorrelation terms. The best place to position the region of interest is on either side of this line of no carrier frequency, preferably leaving this line out of the field of view of the camera and provided that the chirp does not lead to a zero frequency. Depending on which side we position the region of interest, the reconstructed image can appear 'inverted' along the depth axis, as will be shown in Chapter 6.

Figure 5.13(a) and (b) show contour plots of the *maximum* carrier frequency (regardless of sign) and peak width, respectively (units of cycles per scan). These were evaluated within the full volume considered in the simulation for a range of radii of curvature of the illumination beam and for different positions of the pivot axis, as expressed by the OA/R ratio.

Figure 5.13(c) illustrates the different configurations that correspond to OA/R=1, 0.5 and 0.1, with the black dot 'A' indicating the pivot point. In terms of encoding the position of scattering points within the object, it would be beneficial to reduce the peak width as much as possible to ensure optimal depth resolution. On the other hand, the carrier frequency should be high enough to separate the spectral peaks from the DC and autocorrelation terms.



Figure 5.12. Spatial variation of the carrier frequency,  $f_{carrier}(a)$  and the maximum variation in  $f_{shift}$  during a scan, (b) in cycles per scan, as the illumination beam is tilted from -12.5mrad to 12.5mrad around  $\theta_C = \pi/4$  within a measurement volume of 5×5×5mm (only the plane *y*=0 is shown, as there is nearly no variation along the *y*-axis), with R=0.5m and OA/R=0.9.



Figure 5.13. Effect of the illumination angle as it is tilted from -12.5mrad to 12.5mrad around  $\theta_C = \pi/4$ , on (a) maximum carrier frequencies over a range of ratios OA/R in cycles per scan and (b) the maximum frequency shifts at a given point in Fig. 5.10. (c) A visual representation of the pivot point in relation to the diverging illumination beam for the cases OA/R=1 (top), 0.5 (middle) and 0.1 (bottom).

This combination of high carrier frequency and reduced peak broadening is possible, as we can see in Fig. 5.13, for low OA/R ratios, i.e. the pivot axis close to the object, and for small values of R. The latter, however, may introduce complications when the position of the scattering points within a refractive object needs to be retrieved. A more practical setup would involve collimated illumination and low OA/R ratios, although it will become more sensitive to changes in the OA/R ratio. The latter was the case in the full sensitivity TSI system presented in Chapter 4.

## 5.5 Optical aberrations

In a perfect optical system a lens will focus every ray of light from a point located on the object plane to the same point lying on the image plane. Unfortunately there are no such things as perfect lenses and so the rays do not converge to or diverge from a single point. These departures from the ideal are called aberrations and lead to a blurring of the image which ultimately affects any measurements made by the system. As discussed in Section 4.2.3 the full sensitivity TSI system contains many plano-convex lenses in both the reference and object beam paths. Light scattered from the sample is recombined at the plate beamsplitter and focussed though an imaging lens onto the detector. The lens system in the object beam path is of particular concern due to the high number of lenses in series focussing and collimating a beam that moves throughout the duration of a scan. With many lenses in the whole system it is important to investigate possible aberrations which may affect the phase of the illuminating wavefront.

Chromatic aberrations can be ignored since TSI uses only a monochromatic light source and since the system is symmetrical, only aberrations moving along only one lateral axis during a scan are applicable, as shown in Fig. 4.5. Therefore coma, astigmatism and distortion can be ignored whereas de-focus, spherical and field curvature will be taken into consideration. The phase of the reference beam remains constant throughout and ultimately will not affect the interferometric result, therefore only the illumination beam will be considered.

A lens with a higher curvature, i.e. shorter focal length coupled with a smaller diameter, will tend to introduce more significant aberration errors. If the beam propagating through a lens is of a similar diameter then these errors become even more pronounced. As mentioned in Section 4.2.3.4 the diameter of lenses  $L_2$  to  $L_4$  are 25mm and the diameter of the beam propagating through them is 7mm. The diameter of  $L_5$  is 100mm and the beam diameter propagating through it is 28mm.



Figure 5.14. The rays in the de-focus aberration do not converge to a point on the focal plane but instead converge to a point on a different plane.



Figure 5.15. A lens showing an exaggerated spherical aberration. Rays leaving the lens converge to different points on the optical axis, with the rays propagating through the lens further away from the optical axis being focussed more tightly.



Figure 5.16. A lens showing field curvature. Depending on the incident angle of the beam, the rays converge to a point on a parabola.

TSI performs its measurements by tilting the illumination beam thereby altering the rate of change in the phase of the wavefronts arriving at the sample. When the propagating light rays fail to converge at a single point on the focal plane then the phase of the wavefront arriving at the image plane will depend on the illumination angle.

The first aberration to consider is de-focus. The lens focuses the rays to a point on a plane that does not lie on the theoretical focal plane, as shown in Fig. 5.14. The effect observed at the focal plane is that the image becomes out of focus and blurred. The image remains out of focus irrespective of the angle of incidence and independent of the position on the image plane. The simple remedy is to translate the lens along the optical axis until the actual focal point returns to the image plane or, in the case of a camera lens, adjust its settings. If it is assumed that the de-focus aberration cannot be corrected then the beam exiting  $L_5$  will contain the accumulated errors from  $L_2$  to  $L_5$  in the phase of the wavefront. This however is not a problem in TSI; despite the phase errors being compounded with each lens, the errors equally affect the whole beam. Therefore the phase errors are constant and so the change in phase due to the tilting wavefront arriving at the sample remains the same, acting as if there was no de-focus aberration. However the focal point of the beam does not lie on the focal plane and, with the lenses in the object path in series, the beam exiting the subsequent lens will not be collimated, therefore causing a spherical wavefront illuminating the sample. The effects of beam curvature are discussed in Section 5.4.3.

The second aberration to consider is the spherical aberration. The lens focuses the rays onto different points along the optical axis depending on the where they enter the lens: The rays furthest from the optical axis are focussed more tightly and a perfect focal point is never

produced, as shown in Fig. 5.15. The observable effect at the focal plane is a bright spot surrounded by a halo of concentric rings. The blur on the image plane is independent of the position on the image plane or angle of incidence and cannot be refocused. Spherical aberrations can be minimised by having a smaller beam diameter in relation to the lens diameter and also with an optimal lens orientation. Once again, by assuming that the spherical aberration cannot be corrected or minimised then the beam wavefront will gain phase errors with each passing lens and the beam exiting  $L_5$  will contain these accumulated phase errors. Similar to de-focussing the errors equally affect the whole beam, introducing a constant phase error. The rate of phase change in the illumination beam as it tilts through the range will be the same as a beam without any spherical aberration errors therefore not affecting the interferometric result.

The final aberration to consider is the field curvature. Depending on the angle of incidence the rays focus onto a parabola that deviates away from the ideal focal plane, as seen in Fig. 5.16. The observable effect on the focal plane is that the spot will be blurred to a degree depending on its position in relation to the optical axis. The solution to removing the field curvature would be to either use a beam with a perpendicular angle of incidence or locate the imaging plane onto the point of focus.



Figure 5.17. When lenses are in series the field curvature focuses the rays before the focal plane. The converging rays then enter the subsequent lens and are therefore not collimated.
In TSI it becomes obvious that this is not possible in the lens system in the illumination beam path due to the range of the beam tilt during a scan. It can be seen in Fig. 5.17 that when the beam is away from the optical axis during its tilt that the focal point falls short of the focal plane and therefore enters the next lens from beyond its focal point. The result is that the beam leaving the second lens is convergent and with lenses in series, as seen in Fig 4.5, the net effect is a cumulative blurring of the spot, before  $L_5$  leading to a convergent beam that illuminates the sample. The effect of this divergent beam on the phase is discussed in Section 5.4.3. Throughout an acquisiton the beam scans through the tilting range and the focal point gets closer to the lens' focal plane and then moves away again, following the parabolic curve. This results in a piston-like action of the phase of the wavefront that illuminates the sample during the acquisition. This change in the phase leads to a chirp in the intensity signal, similar to the one seen in Fig. 4.8 and has to be dealt with as described in Section 4.3.2. Fortunately, these are quadratic effects that are corrected during complex demodulation.

## 5.6 Summary

Optical elements were included into the setup to reduce intensity modulation due to fibre strain and vibrations. A simple polariser positioned after the output of the optical fibre significantly reduces the variations in the beam intensity entering the system. Thus speckle intensity variations detected at the camera are due to phase changes in the interference pattern as opposed to strain in the optical fibre.

The repeatability of the rotating and tilting stages was investigated to assess the expected degree of spurious displacement that would be obtained during a full-sensitivity measurement. It was shown that rotation of the stage leads to a constant in-plane error of less than  $62.7\mu$ rad, observed by the 1 fringe in the phase difference. The tilting stage shows a repeatability error by the change in phase and has an out-of-plane displacement error of approximately 25nm.

Before performing an acquisition of a depth-resolved sample, it is necessary to find the quadratic term describing the phase of an intensity distribution obtained from flat opaque reference surface. This quadratic term needs to be optimised in order to perform an accurate complex demodulation procedure. This can be accomplished by comparing how the

reconstructed sample thickness compares with different quadratic coefficients and it is dependent on the tilt interval between successive frames.

It was shown that throughout the duration of a scan the speckles do not completely decorrelate. It can be expected that speckles that decorrelate quickly, e.g. due to a small numerical aperture of the imaging lens, would lead to a loss of depth resolution. A better, though more computationally intensive, way to analyse TSI data with a minimum effect from speckle decorrelation is to consider TSI as a 3D linear filtering operation on the object spatial frequencies [103][106].

The effect of the illuminating beam curvature and the pivot axis position was studied and also potential problems that may arise from optical aberrations in the illumination beam. It was shown that the position of the pivot axis and the divergence of the illumination beam have an effect in the loss of depth resolution as a frequency chirp is introduced in the interference signal. The numerical simulation indicates that divergent beams with a short radius of curvature and the pivot axis near the object may provide a good performance in terms of number of independent spatial channels or voxels in the data volume. In order to increase the number of independent axial measurements, given by the ratio between the carrier frequency and the frequency shift throughout the tilt scan, it is desirable to locate the pivot axis as close as possible to the object surface. The effect of the field curvature aberration creates a piston-like effect on the phase of the illumination beam throughout the duration of a scan and also changes the curvature of the wavefront. This aberration, the pivot axis location and beam divergence contribute to a non-constant rate of phase change of the wavefront arriving at the sample.

Chapter 6 present experimental images of depth-resolved reconstructions of various samples, including: 1) a stepped surface profile of a flat opaque aluminium plate; 2) a semi-transparent epoxy bar and 3) a semi-transparent epoxy bar containing internal features. Also presented are phase change images due to rigid body motion including both in-plane rotation and out-of-plane tilt.

# Chapter 6

# Reconstruction of surface and depthresolved structures using TSI

# **6.1 Introduction**

The prototype TSI system presented in Chapter 3 was able to reconstruct depth-resolved cross sections of an epoxy bar from data acquired from just two azimuths on the plane of the optical table, enabling one in-plane (horizontal) and the out-of-plane displacement components to be determined [6]. The small tilting range and non-linearity in the modulation frequency limited the depth resolution to approximately 1mm. The incorporation of the rotation stage in the new TSI system described in Section 4.2 enables the illumination of the sample from any azimuth, allowing the evaluation of the remaining in-plane component and thus achieving full three-dimensional sensitivity. This chapter presents reconstructions obtained with the full sensitivity TSI system of surface profile and cross sections of a number of samples. Expressions of the displacement components as a function of the measured phase changes are also presented and a validation experiment is described in which all orthogonal

components of the displacement field are evaluated within the volume of a weakly scattering sample subjected to controlled rigid body rotations.

## 6.2 Depth-resolved structure reconstructions

Figures 6.1(a) and (b) show a schematic representation of an opaque, optically rough flat aluminium plate with a 0.98±0.01mm step and roughness average (Ra) of 2.35µm. A second sample consisted of a weakly scattering epoxy bar 7.87±0.01mm thick, seeded with titanium oxide particles with an average size of 1µm, well below the dimensions of the point spread function (psf) of the TSI system (29.8µm laterally and 254.7µm axially inside the bar). The particles/resin volume fraction was approximately  $3 \times 10^{-3}$ , which results in nearly 700 particles per psf. If particles were sparse as required by particle image velocimetry [118], there would be regions in the volume that would not contribute any signal and thus no displacement information could be retrieved. On the other hand, a high volume fraction would result in multiple scattering, thus increasing the noise floor and reducing the depth resolution of the system (the point spread function broadens in the axial direction). This is because of the extended optical path due to multiple scattering events, which effectively delocalise the scattering centres. This guarantees that there is intensity modulation at every voxel in the reconstructed volume. Holes with 1mm diameter and 2mm from centre to centre were drilled through the sample in two different arrangements as shown in Fig. 6.1(d) and (e). They were either filled with air  $(n_2=1)$  or glycerol  $(n_2=1.4733)$  to see the effect of refractive index changes within the bar. The bar refractive index was  $n_1 = 1.6574$ , as measured with an Abbe refractometer.

All measurements were performed with the following experimental parameters: central illumination angle  $\theta_c = \pi/4$ rad, total tilting range  $\Delta \theta_0 = 25$ mrad,  $\lambda = 532$ nm,  $n_0 = 1$  and a Hann windowing function,  $\gamma = 4$ . The front surface of all the samples tested was oriented perpendicular to the *z*-axis at the position for which the demodulation parameter was extracted for the reference surface as described in Section 4.3.2.



Figure 6.1. Different samples studied with TSI using illumination wavevector  $\mathbf{k}_i = 2\pi/\lambda(-1/\sqrt{2}, 0, 1/\sqrt{2})$ : (a) An opaque, optically rough aluminium plate with a flat surface and no other features, (b) with a right angle 0.98mm step, (c) a semi-transparent epoxy bar with no internal features, (d) a flat series of holes and (e) a staggered series of holes.

#### **6.2.1 Experimental results**

For each different sample the method of producing the images followed the description in Fig. 4.7. The flat opaque aluminium plate shown schematically in Figure 6.1(a) was reconstructed through complex demodulation and re-registration. A reconstruction of its cross-section is shown in Fig. 4.15. The illumination direction is parallel to the plane of the page.

#### 6.2.2 Step surface profile

Figure 6.2 shows a profile of the aluminium step after demodulation and re-registration. An average FWHM peak width of 150µm was obtained (by averaging along the columns in Fig. 6.2), against the theoretical depth resolution  $\delta z = 120$ µm. The reconstructed step height was 0.99±0.03mm, versus 0.98±0.02mm measured with a Vernier calliper. A sequence of 2501 frames was acquired in 723 seconds, with an illumination beam tilt step  $\delta \theta_0$ =10µrad between frames, which resulted in a depth range of over 37.6mm (from Eqn. 3.13), even though Fig. 6.2 only shows 12mm out of the entire depth range. A data volume with 256×256×312 (height×width×depth) independent spatial measurements was thus achieved, where 312 is the number of voxels over the depth range.



Figure 6.2. Reconstruction of a step profile in the *yz* plane.

#### 6.2.3 Weakly scattering epoxy bar

A sequence of 1667 frames was acquired in 417 seconds, with an illumination beam tilt step  $\delta\theta_0=15\mu$ rad between frames, which resulted in a depth range in the sample of 53mm. The depth resolution predicted by Eqn. (3.10) inside the bar is 255 $\mu$ m. Front and back surfaces of the bar are clearly seen in Fig. 6.3, and indicate a bar thickness of approximately 7.9mm.

The bar was next imaged with the first set of holes (halfway through the bar thickness and parallel to the *x*-axis) in the field of view. The holes were left filled with air. A sequence of 1667 frames was acquired in 417 seconds (~4 frames per second), with an illumination beam tilt step  $\delta \theta_0 = 15 \mu$ rad between frames. Figure 6.4(a) shows the reconstructed bar and the internal structure, averaged along the *y*-axis.

Another acquisition was performed, this time one hole (the one nearest the top in Fig. 6.4(b)) was filled with glycerol, refractive index  $n_2 = 1.4733$ , and the remaining holes were filled with immersion oil,  $n_3 = 1.516$ . This was done in order to reduce the strong scattering at the air-epoxy interface in the holes, which leads to spurious streaks in the reconstructed cross section of the bar, parallel and at an angle to the *z*-axis, as seen in Fig. 6.4(a). Again, a sequence of 1667 frames was acquired at a rate of 4 frames per second, with an illumination beam tilt step  $\delta\theta_0=15\mu$ rad between frames as described earlier.



Figure 6.3. Reconstruction of the cross section (xz plane) of the epoxy bar in a featureless region.



Figure 6.4. Reconstruction of the cross section of the epoxy bar with internal features: (a) flat set of holes filled with air,  $n_2=1.0008$  and (b) filled with glycerol and immersion oil,  $n_2=1.4733$ , 1.516, and 1.516, respectively, for the three holes from top to bottom.

It is important to note that in Figs. 6.4(a) and (b), due to the position of the pivot point, the images are inverted, i.e. the back face of the bar is reconstructed at  $z \approx 0.4$ mm and the front face at  $z \approx 8.5$ mm. When the holes are filled with air, the intensity of the scattered light from the top surface of the holes is much higher than the light scattered back from the remainder of the bar and spurious 'streaks' extend beyond each hole. These streaks, may be caused by secondary illumination of the bar from intense scattering at the hole boundaries. When the holes are filled with glycerol and immersion oil, the reduced scattering in the hole boundaries results in better use of the streaks around each hole are less pronounced. The hole's front boundary looks brighter in the top hole than in the two bottom ones, which is due to the difference in refractive indexes between the epoxy resin, the glycerol and the immersion oil. The holes are easily visible but again appear slightly elongated but not to the same extent as the air-filled holes. This elongation effect is also due to the difference in optical paths in the epoxy and the hole filling substance.



Figure 6.5. Reconstruction of the cross section of the epoxy bar with internal features (the staggered set of holes): (a) filled with air,  $n_2=1.0008$ ; and (b) filled with immersion oil,  $n_2=1.516$ .

The second set of internal features studied was a series of staggered holes to evaluate the effect of depth in the image reconstruction. Each hole was 1mm apart, 2mm between centres – see Fig. 6.5.

The step interval between each beam tilt was  $15\mu$ rad, giving 1667 frames per acquisition. In order to illuminate every hole with no shadowing effects the object beam was directed onto the sample as shown in Fig. 6.1(e). For the first acquisition sequence set, the holes were left filled with air. As before, the bar is barely visible but the top surfaces of the holes are clear and elongated as can be seen in Fig. 6.5(a). Again there are streaks around each hole. Another acquisition was performed, this time with every hole filled with immersion oil. It can be seen in Fig. 6.5(b) that the result is similar to the previous case with the holes at the same depth.



Figure 6.6. An *xz* cross section from within the sample volume of the bar with the flat series of holes flat set of holes filled with glycerol and immersion oil,  $n_2=1.4733$ , 1.516, and 1.516, respectively, for the three holes from top to bottom.

Figures 6.3 to 6.5 show the reconstructed samples averaged along the *y*-axis. The averaging allows the sample to be viewed more clearly due to the speckle noise in the reconstruction. Figure 6.6 shows an *xz* cross-section slice from within the sample. The holes are hardly visible due to the speckle noise. This illustrates the need for averaging along the *y*-axis in order to test the dimensional accuracy of the reconstructions.

One way to improve cross section reconstructions would be to increase the signal to noise ratio in the interference signal (by increasing laser power and optimizing beams intensity ratio) and by utilizing the full dynamic range of the camera.

# 6.3 Full sensitivity depth resolved displacements

#### 6.3.1 Gauge volume

The so-called *gauge-volume* is the region in the sample where all displacement components can be evaluated. Before any phase/displacement calculations are performed it is important to confirm that the region of interest on the reconstructed sample from one azimuth overlaps with the region of interest on the sample from the other azimuths. If this is not the case then it becomes impossible for the change in phase to be measured since each region of interest will

be looking at different sections within the object. Fig. 6.7 highlights a sample with regions of interest in the data volume that do not overlap, with the arrows indicating the usable regions of the data volume. Figure 6.7(a) shows that the unusable data lies in the region between pixels 105 and 256 along the *y*-axis. This part of the data volume serves no purpose and cannot be reregistered due to partial volume reconstruction. The unusable data in Fig. 6.7(b) lies between pixel 1 and 180 on the *y*-axis. A data volume overlap of only 75 pixels in the *y*-axis exists between the two usable regions of interest and therefore a phase change cannot be calculated. In these overlapping regions, there may be a modulated signal present for a given azimuth, but not from the others, thus preventing the combination of the phase components required to obtain the in- and out-of-plane displacements.

Figure 6.8 shows the reconstructed sample set up in a way such that the usable regions overlap. In Fig. 6.8(a) the unusable data is from pixels 220 to 256 along the *y*-axis and the unusable data from Fig. 6.8(b) is between pixels 1 to 62. In this configuration there is a region of 157 pixels that contains an overlap of the modulated interference signal from which the phase changes can be extracted.

Figures 6.7 and 6.8 show the reconstructed cross-sections from opposite azimuths along the y-axis. However it is also important that the data from opposing azimuths along the x-axis overlap. In order to determine the displacement components within the sample volume along all three axes, the phase component along the x-axis must also overlap with that phase component from the y-axis.

Once the gauge volume boundaries has been established, the phase volumes can be reregistered and cropped as described in Section 4.3.3, leaving just the relevant overlapping volume of interest. Each of these volumes now covers the same FOV and frequency range from each azimuth and displacement calculations can then be performed.



Figure 6.7. Example of non-overlapping data from opposing illumination directions: a)  $0^{\circ}$  azimuth and b) 180° azimuth. The arrows indicate the usable regions of interests.



Figure 6.8. Example of overlapping data from opposing illumination directions: a)  $0^{\circ}$  azimuth and b) 180° azimuth. The arrows indicate the usable regions of interests.

#### **6.3.2 Sample characteristics**

A validation test requires careful preparation of the sample, including its scattering properties, dimensions and overall geometry, in order to eliminate as many sources of error as possible. In this case, the sample consisted of a prismatic block made of epoxy resin seeded with scattering particles. The block was manufactured in-house with flat, parallel front and back surfaces, a thickness  $\Delta z = 7.87 \pm 0.01$ mm and refractive index n<sub>1</sub> = 1.6574. The flat

surface ensures that no phase terms due to refraction will contribute to errors in the measured displacement field. The back surface was painted black to reduce internal reflections that would act as extra illumination beams and contribute extra frequency components in the interference signal, leading to ghost reconstructions.



Micrometer

Figure 6.9. Test rig to introduce a controlled 3D displacement field in the sample as a combination of an in-plane rotation (about the *z*-axis) and an out-of-plane tilt (about the *x*-axis).

#### 6.3.3 Rigid body motion

A simple way of introducing a controlled 3D displacement field with simple gradients in the volume of the sample is to combine two rigid body rotations. Figure 6.9 shows the epoxy block fixed on a tilting stage which was firmly mounted on a rotating stage so as to combine their individual movements. The rotating stage rotates at a rate of  $0.01^{\circ}$ /division on a micrometer screw and the tilting stage tilts at a rate of  $1^{\circ}$ / revolution of the control knob. The tilting stage was operated such that an out-of-plane tilt occurs about the *x*-axis.

#### 6.3.4 TSI acquisition parameters

The main experimental parameters were set as follows: 1) central illumination angle  $\theta_C = \pi/4$ rad, 2) illumination beams tilting range  $\Delta \theta_0 = 25$ mrad, 3)  $\lambda = 532$ nm, 4)  $n_0 = 1$  and 5)  $\gamma = 4$ , which corresponds to the use of a Hann sampling window. The front surface of the sample was orientated approximately perpendicular to the *z*-axis and at a position along the *z*-axis for which the demodulation parameter was extracted for the reference surface as described in Section 4.3.2 (DC term reduction and complex demodulation). This ensures that the interference signal demodulation uses the optimum value of *a* so it leads to a sharp reconstruction of the sample features. The axial and lateral resolutions are, according to Eqns. (3.10) and (3.11), equal to 255 $\mu$ m and 29.8 $\mu$ m, respectively. The depth range, given by Eqn. (3.14) was equal to 53.1mm.

#### 6.3.5 Evaluation of displacement components from phase measurements

When the sample is deformed the change in phase for each illumination direction is described in Eqns. (3.18) to (3.21). The combinations of azimuth angle pairs of phase changes provides phase information of the in-plane and out-of-plane phase changes along each orthogonal axis and consequently the displacement along each lateral direction: The difference between the azimuth angle pairs give the in-plane *x* and *y* phase components - see Eqns (3.22) and (3.23) respectively; and the sum gives two independent phase measurements of the out-of-plane component – see Eqns. (3.25) and (3.26). The displacement components, in terms of the phase change, are given by Eqns. (3.27) to (3.30).

With the micrometer on the rotating stage producing a minimum rotation of  $0.01^{\circ}$  (174.5µrad), over a FOV of  $7.73 \times 7.36$ mm the maximum relative in-plane displacements are 1.35µm and 1.28µm in the *x*- and *y*-directions respectively. Eqns. (3.27) and (3.28) yield an in-plane displacement of 376nm/fringe therefore the expected number of fringes across the FOV are 3.59 and 3.40 in the *x*- and *y*-directions respectively. Eqns. (3.29) and (3.30) yield an out-of-plane displacement of 156nm/fringe. If one complete revolution of the control nob on the tilting stage produces a 1° tilt then a 1° revolution produces a 2.78×10-3° (48.5µrad) tilt. Over the FOV the maximum relative out-of-plane displacement is 357nm, equivalent to 2.29 fringes along the *y*-direction.

#### **6.3.6** Phase difference volumes

Figures 6.10 and 6.11 show the differences between the phases for the initial and the deformed states at each azimuth. The phases are wrapped with the white-coloured regions representing a relative phase change of  $+\pi$  and the black regions  $-\pi$ . The slanted edge at the right hand side of each phase map is an effect resulting from the re-registration process; the evenly-coloured grey area to the right of the slanted edge is a region of no data within the phase volume due to the tilt from the Fourier transform. The gradient of this slanted edge in Fig. 6.10(c) is equal and opposite to Fig. 6.10(b) due to phase maps being from opposing azimuths; this same effect can also be seen in Fig. 6.11 but along the *x*-axis.

Both Figs. 6.10 and 6.11 display blurred edges of the sample. One possible cause of this effect is the complex demodulation process. The quadratic coefficient term, a, was an averaged value over the whole FOV. Slight variations from this average are highly likely for each pixel and therefore the image will not be perfectly sharp. The figures also show data outside the edges of the sample. Multiple reflections between the surface edges contribute to higher frequencies that can be seen as fringes to the right of the sample in Figs. 6.10(c) and 6.11(c).



Figure 6.10. *yz* cross-section of the re-registered phase difference volume between the initial and final states after rotation and tilt of the epoxy block for different azimuth angles: (a) A visual representation, (b)  $\alpha = 0^{\circ}$  and (c)  $\alpha = 180^{\circ}$  corresponding to Eqns. (3.18) and (3.20) respectively.





Figure 6.11. *xz* cross section of the re-registered phase difference volume between the initial and final states after rotation and tilt of the epoxy block for different azimuth angles: (a) A visual representation, (b)  $\alpha = 90^{\circ}$  and (c)  $\alpha = 270^{\circ}$ , corresponding to Eqns. (3.19) and (3.21) respectively.

(a)

#### 6.3.7 Evaluation of displacement components

The difference between the phases in Fig. 6.10(b) and (c) is found using Eqn. (3.22), yielding the in-plane phase change component along the *x*-direction, as shown in Fig. 6.12(a). This process is repeated for Fig. 6.11(b) and (c), yielding the in-plane phase change component along the *y*-direction that can be seen in Fig. 6.12(b). Approximately 3.47 fringes can be seen in Fig. 6.12(a) and approximately 3.33 fringes can be seen in the Fig. 6.12(b) representing displacements of  $1.31\mu$ m and  $1.25\mu$ m along the *x*- and *y*-direction respectively. These values correspond to the expected values due to the introduced rotation. The phase volume was convolved with a kernel of  $7 \times 7 \times 7$  pixels, blurring the image and thus reducing noise. This experimental value is close to the expected amount and the small discrepancy may be due to backlash or inaccuracies in the micrometer screw controlling the rotating stage. The unwrapped in-plane displacement is shown in Fig. 6.13.

Two out-of-plane values can be calculated using Eqns. (6.8) and (6.9). The phase from Fig. 6.10(b) was summed with the phase from Fig. 6.10(c), yielding the out-of-plane displacement component using the phase obtained along the *x*-lateral direction, as shown in Fig. 6.14(b). This is repeated using the phases from Fig. 6.11(b) and (c) to yield the out-of-plane displacement component from the *y*-lateral direction and this can be seen in Fig. 6.14(c). Again a  $7 \times 7 \times 7$  pixels kernel was used to convolve the phase volume. Approximately 8.5 fringes can be seen along the *y*-axis in each diagram, giving an out-of-plane displacement of 1.33µm (181µrad tilt) over the 7.73 × 7.36mm FOV, compared to an expected value of 0.357µm (48.5µrad tilt). The matching shape and number of fringes of fringes show an equal out-of-plane displacement regardless of which lateral direction the acquisition was performed. This also demonstrates repeatability of the full sensitivity TSI system.

The large discrepancy between the out-of-plane expected and obtained values may be down to several factors. It is important to remember that 1 fringe represents 156nm of displacement. There is a degree of inaccuracy in the screw of the knob controlling the tilting stage and it is also difficult to measure 1° of rotation, therefore an extra degree of rotation may have been inadvertently added due to human error. Another factor to consider is linear thermal expansion; the knob is made of brass and was rotated by hand, creating the possibility that the temperature of the brass was increased. Brass has a linear thermal expansion coefficient of  $18.7 \times 10^{-6}$  m/m°C and the knob is approximately 10mm long. The amount of linear expansion is given by

$$\Delta l = l\alpha_l \Delta T \tag{6.14}$$

A change of just 1°C in the brass would increase the length of the knob by 187nm, around the order of 1 fringe worth of displacement. Thermal expansion thus seems insufficient to explain the observed discrepancies.



Figure 6.12. Wrapped phase obtained from opposite azimuths corresponding to the in-plane displacement along the a) x-direction and b) y-direction, corresponding to Eqns. (3.22) and (3.23) respectively.



Figure 6.13. In-plane displacement along the a) *x*-direction and b) *y*-direction, with displacement rms values of a) 19.8nm and b) 15.4nm.



Figure 6.14. The out-of-plane displacement from the combination of phases from the a) x-direction and b) y-direction, corresponding to Eqns. (3.25) and (3.26) respectively.

#### 6.3.8 The average out-of-plane phase component

Both phase maps in Fig. 6.14 show almost exactly the same number of fringes and in almost exactly the same position, indicating that the out-of-plane deformation measured along the y-direction is consistent with the out-of-plane deformation measured along the x-direction. To find the average measured displacement between the two out-of-plane phase components

they were unwrapped, the mean calculated and the results are shown in Fig. 6.15. The areas in Fig. 6.15(b) and (c) where z > 9.5mm are the areas of phase noise and are not part of the sample cross section.



Figure 6.15. Average out-of-plane displacement from the combination of the unwrapped phases from the individual x- and y-direction measurements. Displacement rms values for each 'slice' in the phase volume were calculated at (a) 5.50nm (b) 9.01nm and (c) 9.01nm.

#### 6.3.9 Second test to validate the out-of-plane displacement

As described in Section 6.3.7 the number of fringes on the out-of-plane measurement was significantly higher than was expected and consequently the measured out-of-plane displacement was also greater. Environmental factors and human error were suggested as possible, but insufficient, causes to explain the observed differences.

A new experiment was carried out from just two azimuths,  $\alpha = 0^{\circ}$  and  $\alpha = 180^{\circ}$ , thus halving the acquisition time. The sample was moved using a controlled tilt of 48.5µrad about the *x*axis, as before, however there was no in-plane rotation, simplifying the experiment to check the validation. Since one fringe represents a displacement of 156nm, inaccuracies in the tilting of the sample are easily introduced when turning the control knob and therefore extra care was taken to ensure that the control knob of the tilting stage was not turned more than required and was held at ambient temperature

Eqn. (3.30) gives the out-of-plane displacement as 156nm/fringe, and for a FOV of 5.91mm  $\times$  7.03mm a displacement of 341nm is expected, corresponding to 2.19 fringes. Figure 6.16 shows the results of the new experiment. Approximately 2.27 fringes can be seen in Fig. 6.16(a) along the *y*-axis corresponding to a deformation of 354.8nm (50.5µrad); the unwrapped phase change can be seen in Fig. 6.16(b). With the new value being close to the expected amount this is a significant improvement of the results seen in Section 6.3.7.

A possible reason for the improvement includes the reduction of environmental factors affecting the interferometric result due to a shorter acquisition time. Importantly the control knob on the tilting stage was never directly handled in order to increase the accuracy of the introduced tilt and to prevent inadvertent heating.



Figure 6.16. The out-of-plane displacement from the combination of phases from the *y*-direction, corresponding to Eqn. (3.26). (a) shows the wrapped phase and (b) shows the unwrapped displacement with an rms value of 3.85nm.

### 6.4 Summary

The performance of tilt scanning interferometry has been demonstrated in the case of both surface profile measurement and tomographic imaging of a weakly scattering material with and without internal features. The reconstructed sample images show that the volume reconstructions are dimensionally correct and represent the actual structure of the object. The profile and height variation of a stepped surface was detected by the TSI system to be within 0.01mm of the measurement of a Vernier calliper. Internal holes in an epoxy bar were measured to be 1mm in diameter in the reconstructed images, consistent with their actual dimensions. By matching the refractive index in the hole's volume closer to that of the bar, they become more visible in the reconstruction of the cross section due to the resulting reduction of secondary scattering effects.

A demonstration of 3D full sensitivity tilt scanning interferometry was also performed. Controlled experiments were carried out, which consisted of measuring phase gradients due to known rigid body rotations of the bar. In-plane and out-of-plane sensitivities of 376nm/fringe and 156nm/fringe were obtained, respectively. The full capabilities of the TSI system were thus explored, achieving the measurement of all the components of the displacement field inside the volume of a semi-transparent scattering material with interferometric sensitivity. Phase volumes were convolved using a  $7 \times 7 \times 7$  pixel kernel, leading to a number of independent displacements measured within the gauge volume of  $36 \times 36 \times 44$  or  $57 \times 10^3$  voxels. In-plane displacements have been shown to be in accordance with the expected amount and displacements of 1.35µm and 1.28µm were achieved along the x- and y-direction respectively. This difference between the x and y values is due to the size of the FOV being unequal in the x- and y-directions; however the displacement is proportional as expected of a rigid body rotation. The first validation test achieved a measured out-of-plane displacement of 1.4µm over the FOV - significantly higher than the expected amount. Possible causes were discussed including the inaccuracy of the tilting stage and environmental factors due to the handling of the control knob and a long acquisition time. A second validation test was performed with just an out-of-plane tilt displacement. By performing the scans from only 1 azimuth angle pair the acquisition time was shorter, thus reducing environmental influences. The control knob was never directly handled enabling a more accurate sample tilt. The results obtained show an out-of-plane tilt of 354.8nm, which

lies within 4% of the expected amount and confirms that the previous discrepancies were due to an incorrect 'expected' value.

The next chapter provides a summary of the thesis and presents ideas for further investigation based on the findings of this experimental work.

# Chapter 7

# Conclusions and further work

## 7.1 Summary of the thesis

Optical coherence tomography and related techniques (e.g. wavelength scanning interferometry), proved very successful in providing volume reconstructions of semitransparent scattering materials. However, only recently some research effort was put towards measuring depth-resolved displacement fields for mechanical and material science applications. Even though most were able to measure only out-of-plane displacement components, a few focused on the in-plane ones, suggesting that multiple symmetrical illumination directions would allow the measurement of both in-plane and the out-of-plane components [55][74]. 3D full sensitivity measurements had only been performed once recently, by using WSI [100]. This used multiple symmetrical illumination directions and frequency domain multiplexing to obtain both in-plane components as well as the out-of-plane for the measurement of 3D displacement fields. However, like all technologies using broadband light sources, this suffers from dispersion and absorption. Single wavelength technologies were also investigated, such as tilt scanning interferometry, angular spectrum scanning and Lauer microscopy. While the latter is unable to measure displacements due to a forward scattering detection configuration, angular spectrum scanning has only been used for areal profilometry. TSI, when first proposed, proved its ability to reconstruct sub-surface sample structure and also to provide depth resolved displacements with interferometry sensitivity (axial and one transverse component).

The working principles of TSI were presented and the first prototype system was described in Chapter 3. The limitations brought about by the design and hardware were highlighted and taken into account when designing a new system, subject of this Thesis: The main limitations were the lack of full sensitivity capability, poor depth resolution and lack of repeatability due to an imprecise tilting mirror control. Full sensitivity was achieved in this Thesis by incorporating a rotating stage, enabling multiple symmetrical illumination directions and the depth resolution was greatly improved by increasing the tilting range of the illumination beam, as described in Chapter 4. A greater experimental repeatability was achieved by utilising a closed loop pzt-controlled tilting mirror, which also had the advantage of an increase in the tilting range, while an increased gauge volume was obtained by positioning the pivot axis of the illumination beam on the sample. With the new TSI system, for a semi-transparent epoxy bar, a depth resolution of 254.7µm and a depth range of 53.1mm was achieved.

An acquisition performed on a flat, opaque aluminium plate showed that a frequency chirp is present in the detected intensity distribution and becomes more pronounced over a large tilting range. By a process known as complex demodulation the quadratic term in the phase was removed, eliminating the chirp and thus narrowing the peak in the Fourier transform. Before a sample is scanned, a reference surface must be scanned for the purpose of determining the quadratic coefficient.

The reconstructed sample from the demodulated Fourier transform appears tilted due to the backscattered phase being dependent on the lateral position from which it is being measured. In order to measure the phase difference after a sample deformation, a process known as reregistration must be carried out, since phases acquired from opposing azimuths appear reversed. The gauge volume is taken from the re-registered phase volumes that overlap from phases from other azimuths. Re-registration also has the benefit of reducing distortion in cross-section reconstructions.

Chapter 5 presented an evaluation of the system performance. The stability of the beam intensity was investigated. The repeatability of the system was examined by investigating the

effect of the tilting mirror and the rotation stage on the measured phase fields in the case of a static sample. The tilting mirror phase error was small, contributing a partial fringe out-of-plane error (25nm) and the rotation stage contributed up to 1 fringe (62.7 $\mu$ rad) in-plane error across the FOV. Speckle decorrelation was investigated and it was found that the speckles never fully decorrelate for the tilt scan range used.

The effect of beam divergence, pivot axis of the illumination beam and optical aberrations were investigated. Field curvature aberrations in the lenses in the illumination beam path create a piston-like effect on the phase and a change in beam divergence of the beam throughout the duration of a scan. Throughout a scan of the tilting angle a divergent beam numerical simulation was found to add a quadratic term to the phase due to the non-linear rate of phase change measured from a point within the sample, ultimately leading to loss of depth resolution due to a broadening of the peak in the Fourier transform. By positioning the pivot axis as close as possible to the object surface the frequency shift can be reduced.

Chapter 6 presented the depth-resolved reconstructions of both opaque and weakly scattering samples. A height of a stepped sample surface was found to be accurate to within 0.01mm to measurements from a Vernier calliper with a depth resolution of  $\delta z = 120 \mu m$ . The cross-section of a semi-transparent epoxy bar was imaged with and without internal features, with a depth resolution of  $\delta z = 254.7 \mu m$ . These internal features were imaged clearly however spurious streaks extended from each feature due to the secondary illumination of the bar from intense scattering at the hole boundaries. The reduction of these streaks was achieved by matching the refractive index closer to that of the epoxy bar. It is also important to note that the due to the position of the pivot point, the images were inverted.

3D full sensitivity phase changes due to sample displacement were also presented and validated. In-plane sensitivity was achieved at 376nm per fringe. Displacements measured in both lateral directions were found to be effectively equal relative to the FOV. The out-of-plane sensitivity was calculated to be 156nm per fringe. The out-of-plane displacements were measured from both orthogonal azimuths and found to be nearly equal. Averaging lead to a displacement field with reduced rms noise.

### 7.2 Suggestions for further work

The technique described in this project has been aimed to developing a feasible 3D full sensitivity optical method that is able to measure depth-resolved displacement in semi-transparent scattering samples. Several issues were identified that would benefit from further investigation.

Due to the large tilting range of the new TSI system, a quadratic chirp appears in the intensity signal. The broadening of the peaks in the Fourier transform was encountered in the prototype system but, due to the limited tilting range, the nature and cause of this effect was not able to be determined and the authors employed a simple linearisation routine by extrapolating non-linear data points from the intensity signal to narrow the peaks [6]. Angular spectrum scanning also encountered a similar problem but employed a non-linear rate of change in the radius of the ring source/incidence angle to counter this effect [108]. Now that the nature of the chirp is known, it should be possible to extend a non-linear interval between successive mirror tilts. An acquisition is still required to be performed on a flat opaque reference surface in order to determine the coefficients describing the phase of the intensity signal as it changes with the illumination angle. Once these coefficients are known, the rate of the mirror tilt could be programmed such that a linear phase change is obtained from a sample acquisition, thus eliminating the need for the complex demodulation process.

It was found that speckle decorrelation seems likely to pose a limit to the depth resolution when the interference signal is processed for each pixel independently from the others by Fourier transformation along the time axis. This limitation could be overcome by performing a full 3D analysis in k-space based on a description of TSI as a linear filtering operation. So far k-space processing has been attempted on TSI-obtained sample intensity data. Problems encountered included the appearance of phantom images on the sample reconstruction, which in itself appears tilted and this effect has not yet been interpreted. Data processing is computationally intensive and forces significant reductions in the FOV or number of frames, therefore reducing the depth range. The performance of the traditional 1D Fourier transform method, as demonstrated in this thesis, could also be compared to the 3D k-space method, including the spatial resolution and the effect of noise in the reconstructed cross-sections such as the streaks seen coming from the internal features.

The depth-resolved cross-sections of the epoxy bars containing internal features included a sample with a staggered set of holes. The illumination was set up such that the holes were fully illuminated by the incident beam. The effects of shadowing on semi-transparent features have not been explored. It is proposed that further experiments are performed on the epoxy bar with the holes set up in a shadowed illumination orientation.

Considering the new TSI system itself, improvements can always be made in the performance. Whilst it can be said that every component can be improved, e.g. better lenses to reduce aberrations or a tilting mirror with a larger tilting range to improve the depth resolution, a significant issue that should be addressed is the time taken to a scan a sample. Currently a single scan from only one azimuth takes over 5 minutes; the time taken to perform a full sensitivity displacement measurement is at least 40 minutes. Increasing the camera acquisition rate and mirror tilting speed would not only reduce the acquisition time, but ensure the system is less susceptible to environmental conditions, such as temperature fluctuations or air flow. Currently, the rotation and tilting stages and the camera are controlled by the PC. Whilst this simplifies control, it does create a small delay each time the PC waits for inputs buffers to receive 'ready' signals. This is fine for the rotating stage but the frame acquisition rate is determined by the tilting mirror and the camera. By careful programming and the synchronisation of the camera to run on the clock timer of the tilting mirror, the time taken for a single scan could improve dramatically. The logging of the acquired intensity is currently frame by frame. The acquisition can also be sped up by logging the each frame into the camera RAM, as opposed to logging each frame to the PC RAM. This would remove the waiting time for the PC input buffers to receive each acquired frame.

A camera with a larger dynamic camera would allow more intensity levels of light to be detected. This is important in that a more intense illumination beam could be used so that the individual slices within the reconstructed sample volume could be imaged with less noise, thus allowing features such as bubbles to be reconstructed.

This thesis presented an attempt to measure 3D full sensitivity displacement in depthresolved samples. This method employs an interferometric method using a tilting monochromatic illumination beam. It was demonstrated that the 3D full sensitivity TSI system has great potential in the field of depth-resolved imaging and displacement measurement. The next logical step would be to measure true deformations due to a mechanical load as opposed to rigid body motion, as used in the validation tests. These measurements could be used to determine material position dependent properties such as the Young's modulus via inverse methods as mentioned in Chapter 1. However, the main drawback of TSI (or any other method of scanning the incident angle of the illumination beam) is the level of computing required when the sample has a curved surface, such as that of a human cornea. The angle of the refracted illumination beam becomes position dependent and therefore the phase will change in a non-linear way. This would require time consuming refraction correction algorithms, further increasing the data processing time. One possible solution to counter this would be to immerse the sample in an index-matching fluid inside a specially designed containment chamber; however this would negate the non-contact advantage of optical techniques. This would limit TSI to the measurement of object with flat surfaces. Due to the current time required for a single acquisition, TSI would be useful to measure materials such as fibreglass composites, polymers, or *ex-vivo* tissues, e.g. artery walls, cornea, or skin.

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