Handbook of Speckle Interferometry

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Preface

Optics laboratory practices are the best way to understand the laws of physics that control the properties of electromagnetic waves and the way they interact with matter. As students start their journey on this science and perform optics experiments to harness the light features, it is always exciting to understand the mechanisms that allow us to measure physical properties using light. Light is everywhere and is part of our meaningful life. For the author, interacting with the universe through the use of light has been a joy and a journey of discovery. One of the aspects of electromagnetic waves that is most disconcerting is its interaction with rough surfaces that produce so-called speckle. This book is written for students who enjoy lab practices and look forward to dealing with, and understanding, speckle properties to find new ways of using them for measurement purposes.

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Scientific societies depend on lots of people interacting and building up knowledge in some particular area. However, it is only possible to acknowledge a few of those who contribute or help to complete a book like this. In my case, I shall name the few who contributed to my optics education. When I started studying optics for the bachelor degree, J. C. Ruiz was the first teacher who demonstrated optics experiments at the F.C.F.M.; thank you J. C. for your initial guidance. For my MSc studies, the professors at the Physical Optics department at CICESE were responsible for instructing me on the world of optics; thanks to all of you, but especially to J. E. A. Landgrave and H. Escamilla for allowing me to learn the interferometry and physical optics theories. During the early years of my research, the influence of D. Malacara at CIO helped me start my professional development; many thanks to Daniel. Still, it was during my PhD studies that the staff of the Mechanical Engineering department at Loughborough University taught me the speckle interferometry techniques that I will be describing and updating in this book. From my PhD days, I shall always be grateful to D. Kerr, J. M. Huntley, P. D. Ruiz, J. Tyrer, and J. Coupland for their help with comments or insights from previous research. Their comments and discussions were

fundamental to building the accumulated knowledge that I used as a basis for my research in this optics area. I also thank my first colleague in this area, and now a dear friend, G. Kaufmann; thank you Guillermo for participating in our early research. I also acknowledge R. Mendoza for creating the graphics of several figures. I thank Dara Burrows for her talent and skill in editing the final version of this book. Finally, I would like to express my most sincere acknowledgements to my wife Lucy and my daughter, who help me by being supportive and encouraging me to persist until my dreams become real.

Motivation

Speckle interferometry techniques have been evolving since they were first developed, producing a range of tools for several applications in industry and research. Nowadays, there is a set of well-established methods, but still, the most recent ones are not yet comprehensively documented. A review of the speckle techniques in terms of simple concepts such as carrier fringe patterns allows easy comprehension of the speckle phenomena, including digital holography techniques. Carrier fringe patterns can always be replaced by phase-shifting methods when the experiments are limited to closed-fringe patterns. Following the main emerging industrial and biomedical applications, the chapters included in this work also present the most recent research in this area.

The initial growth in speckle phenomena applications began after the advent of the invention of the laser, which was the first source of coherent light produced and tested in the initial experiments by illuminating rough surfaces [1]. At the beginning of laser light utilization, experimental observation speckle phenomena showed a granular structure that could be visually associated with noise. Even though the same noise characteristic was observed long before the laser invention [2], the cameras and TVs needed to expand speckle applications were not readily available until the 1960s. However, one similar noise that was known at the time was the noise that appears when a TV is tuned without a signal, showing an image with white and dark pixels randomly distributed that changed in time without any apparent cause. Later discoveries from the background cosmic radiation caused by the Big Bang explained the radio signals that were detected by the TV antenna; the radiation caused by random interference produced the speckled patterns on the TV screens. Nonetheless, the idea of speckle as noise stagnated, and it took a few decades after the laser invention for it to be considered as a non-noisy signal that could be used routinely as a measurement tool.

To remove the noise characteristics of speckle patterns, the first research on speckle techniques required dark rooms, specialized anti-vibration tables, and isolation from thermal air currents. These requirements caused the techniques to be branded as difficult to implement and limited the number of applications. Even now, interference techniques still present the same constraints, but standard interferometry equipment used to avoid inaccuracies in their measurements is available using off-the-shelf optics components. Nonetheless, as speckle techniques evolved, some noise continued to be challenging to remove, such as speckle decorrelation, which, to this date, is still challenging to control for displacement measurement and persists as one of the main drawbacks to the attainable precision of these techniques. Health hazards, on the other hand, remain when optical setups include high-power lasers for speckle-generating techniques, and the reader should be aware of the training required and safety measures (see, for example, Ref. [3]) while implementing the techniques described in this handbook.

Objectives

This handbook presents a review of speckle interferometry techniques ranging from works from the early 1990s [4–7] to more recent works [8–17]. However, in this new compilation of speckle interferometry techniques, the main aims are as follows:

- To explain the speckle techniques. The reader is introduced first to simple direct phase-measuring techniques based on carrier fringe patterns, also known as open fringes. These techniques give an instantaneous phase from a single fringe pattern, removing bias and modulation problems usually found when phase-shifting procedures process non-carrier interference fringe patterns. As the procedures needed for phase extraction from closed fringes rely on spatial or temporal phase-shifting procedures, its implementation depends on the kind of technology implemented in the experimental setups.
- To explain the evolution of speckle interferometry techniques based on similar digital holography principles.
- To summarize the main electronic speckle pattern interferometry (ESPI) techniques under a simplified mathematical notation that includes rigid body displacements, together with standard body displacements through the adoption of an object’s pose with six degrees of freedom.
- To promote the adoption of temporal phase unwrapping instead of spatial phase unwrapping.
- To present a summary of recent industrial applications.
- To include a short review or update of the recent research in ESPI.

The material in this handbook is a helpful introduction to speckle techniques for non-specialists, and readers will benefit from the insight and understanding of the basic speckle interferometry principles presented here.

Chapter 1

Fundamentals of Interference

1.1 Interference

The electric amplitude of the simplest plane wavefront propagating along the z direction is given at the position (x, y, z) and time t by the following equation:

$$E(x, y, z, t) = a\cos(wt - kz), \tag{1.1}$$

where the electric oscillations are the same for each coordinate (x, y) and are therefore omitted; a is the wave amplitude; $k = 2\pi/\lambda$ is the wavenumber; w is the angular frequency, which can be expressed in terms of light frequency ν as $w = 2\pi\nu$; and λ is the wavelength. The previous equation can be represented using complex numbers:

$$E(x, y, z, t) = \mathrm{Re}\{ae^{i(wt-kz)}\}, \tag{1.2}$$

or by

$$E(x, y, z, t) = \mathrm{Re}\{Ae^{iwt}\}, \tag{1.3}$$

where $A(x, y, z) = ae^{-ikz}$ is the complex amplitude. The spatial dependence on z is frequently expressed in terms of the spatial phase $\phi = kz$, in which a displacement $z = \lambda$ is equivalent to a phase change of 2π. Usually, the spatial phase is the *only variable of interest* in interferometry, as the conventional detectors such as a camera or photodiodes are not able to register the temporal fluctuations that are usually integrated in time to give [18]

$$< E^2(x, y, z, t) >= \frac{A(x, y, z)A^*(x, y, z)}{2} = \frac{a^2}{2}. \tag{1.4}$$

Therefore, the detection from the spatial complex wavefront is expressed by the integral in time, which is also $< E^2(x, y, z, t) >= |A(x, y, z)|^2/2$ and is known as intensity (denoted by I in this book). Note that the intensity $I = AA^*/2 = a^2/2$ is a real value caused by the spatial phase and the time

1.3 Laser Properties

In the simplest case of a laser with a linear cavity and two mirrors, the laser bandwidth will depend on the bandwidth of the gain medium. As a typical example, the HeNe laser has a central wavelength λ_0 with a 1.5 GHz gain bandwidth, which causes a spread of wavelengths given by the following equation:

$$\Delta\lambda = \frac{\lambda_0^2 \Delta\nu}{c}, \tag{1.10}$$

c being the speed of light; therefore, the HeNe emission at $\lambda_0 = 633$ nm has a width of $\delta\lambda = 0.002$ nm. Another example is the Ti:sapphire laser, which has a $\Delta\nu = 128$ THz gain bandwidth media, causing a wavelength spread of 273 nm at 800 nm, which is much broader than that of HeNe. As interference can be sampled using a constant-wavenumber ratio, a convenient sampling ratio is given by

$$\delta k = 2\pi \frac{\delta\lambda}{\lambda_{\mathbf{0}}^2}. \tag{1.11}$$

Now within the large wavelength spread of Ti:sapphire exist emission modes that depend only on the cavity length of the laser. In the case of a linear cavity, there are modes given at the frequency

$$\Delta\nu = \frac{c}{2L}, \tag{1.12}$$

where L is the cavity length. For example, a cavity length of 30 cm will produce modes at a frequency of $\Delta\nu = 0.5$ GHz, each mode using Eq. (1.10) with a spread of 1 pm. When many modes of the cavity interfere due to the phase changes induced by thermal changes, the laser is called continuous wave (CW).

1.4 Speckle Fundamentals

There are two kinds of speckle: objective and subjective (see Fig. 1.1). The autocorrelation function of speckle intensity [19,20] is given by

$$C(\zeta, \eta) = \left| \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} S(x, y) e^{ik\frac{(\zeta x + \eta y)}{z}} dx dy \right|^2, \tag{1.13}$$

Chapter 2

Speckle Interference and Displacement

Assuming the use of long-coherence-length light $\gamma = 1$ and the introduction of phase shifting, the interference obtained from ESPI interferometers can be reduced to the addition of two beams R and S that differ in their randomness characteristics according to

$$I(x,y) = I_R(x,y) + I_S(x,y) \\ + 2\sqrt{I_R(x,y)I_S(x,y)}\cos(k\Lambda(x,y) + \phi_r(x,y) + S_q), \tag{2.1}$$

where I_R and I_S are the intensities of the two beams: a reference beam R and a static beam S; k is the wavenumber; Λ is the OPD produced by a laser-illuminated object; $\phi_r(x,y)$ is a random phase generated from the light scattered by the object or a reference beam; and $S_q = (q-1)\pi/2$ when four phase shifts ($q = 1,2,3,4$) are used. As Sections 3.2 and 3.3 will show for two types of interferometers, if the phase term $k\Lambda(x,y)$ includes the phase terms introduced by object displacements and rigid body movements due to three rotations, it can be described by

$$k\Lambda(x,y) = kn(\mathbf{r}_R - \mathbf{r}_S) \cdot \Theta, \tag{2.2}$$

where $k\Lambda(x,y)$ is the phase, k the wavenumber, n is the refractive index, $\mathbf{r}_R$ and $\mathbf{r}_S$ are the observation and illumination vectors, and Θ is the 6D pose, given by

$$\Theta^T = \mathbf{R}\mathbf{d}^T, \tag{2.3}$$

where T denotes the transpose, $\mathbf{R}$ is a rotation matrix that includes three rotations at rotation angles α, β, γ around three axes as shown in Fig. 2.1, and $\mathbf{d} = (x + x_0, y + y_0, z + z_0)$ is the displacement and translation vector that includes three diplacements and the three translation movements x_0, y_0, z_0 for a total of six degrees of freedom per pose. This phase can have different representations, depending on the kind of ESPI interferometer used; the main

2.4 Practical Removal of Environmental Instabilities

Environmental fluctuations in practical ESPI can be divided into two primary instabilities: mechanical drifts and thermal drifts. Unless perfect isolation of mechanical vibrations and thermal air currents is achieved in laboratory experiments, most ESPI or holographic experiments will present real-time phase changes that reduce the precision of the final measurements. Under these conditions, real-time phase extraction benefits from including linear phase removal techniques or phase extraction algorithms such as the Carré algorithm that have shown to be appropriate for removing the linear induced phase. However, the speckle decorrelation phenomena removes and introduces speckle in the optics aperture due to object tilt, and the Fourier shift theorem explains the speckle shift in the aperture corresponding to the object tilt. Its noise effects are mainly reduced by low-pass filtering, or re-referencing when the object tilt displaces the speckle in the ESPI aperture by up to 8% of its diameter, or by changing to a five-step phase-extraction method, depending on the noise characteristics [54]. An alternative method could take into account and re-introduce the speckle phase after the tilting of the object under investigation in the aperture of the optical system. But first, experimental tilt detection in real-time should be addressed to implement stable-phase re-correlation.

Further phase distortions can be generated from the speckle pattern capture and processing algorithms. In the speckle pattern acquisition, the nonlinear response of the cameras and electronic noise, including analog-to-digital conversion, can introduce uncertainties in the light intensity. And once the digital intensity is saved in the computer, algorithms or computer precision can add additional phase uncertainties. Therefore, besides the camera aberration corrections, a camera gray-level calibration is needed to obtain a corrected linear intensity. As is well known, a speckle exponential intensity distribution is obtained when laser back-reflected light from a rough surface is acquired in a camera detector. This distribution will produce a large number of pixels with zero intensity, and a few with high-intensity values that always saturate the gray levels obtained after the analog-to-digital conversion. Some optical setups produce the exponential type of speckle intensity distribution that can be changed by speckle integration in the camera pixels.

A nonlinear phase that oscillates around an average phase value due to thermal drifts is, therefore, an everyday experience when using ESPI interferometers. Then, if the instantaneous phase is obtained by digital holography, its phase values represent samples from an unknown, constantly changing, nonlinear phase. Still, there are phase-stepping algorithms that can remove local linear phase changes, such as the temporal Carré method, which more effectively reduces phase oscillations and improves the overall phase tracking.

Chapter 3

Electronic Speckle Pattern Interferometers

There are three basic optical setups for electronic speckle pattern interferometers (ESPIs) that measure object displacements but are restricted to measuring a few of the possible six degrees of freedom. Three of these interferometers will be described in the next three sections. Their optical setups have been successfully combined to achieve the measurement of additional degrees of freedom [55]. For simplicity, all of the illuminations in the interferometers are assumed to be collimated. Still, as was pointed out in Ref. [56], the divergent light introduces additional constraints that need to be addressed in these kind of interferometers [57–60].

3.1 Out-of-Plane Electronic Speckle Pattern Interferometer

As shown in Fig. 3.1 the basic out-of-plane ESPI setup makes use of the intensity registered in a CCD camera (image plane) by the interference of a speckle field (reflected light from the object) and a reference beam that is formed by focusing the light using L2 and L3 over the lens L1 aperture. Several phenomena are involved in the interference patterns produced by this kind of optical setup: depolarization, decorrelation, and spatial or temporal coherence. Some of these phenomena were reduced by introducing appropriate optics in the initial commercial designs [61]. First, the speckle field is generated by the light reflected from a test object (O) and collected by a lens (L1) with a small aperture. This light and the size of its aperture determine the speckle size. Second, the reference beam can be produced in several ways, with different geometrical arrangements for interference with the object speckle field (for simplified ESPI setups, see Refs. [62–66]), but the setups presented here have shown to give experimentally high-contrast ESPI correlation fringes. Furthermore, the reference beam can have different intensities or wavefront shapes. Third, maximum interference visibility is possible only if the light arriving from the object has followed the same optical path as the

$$h(x,y) = \frac{\lambda}{2\beta \sin\theta}. \tag{3.23}$$

Therefore, the β rotation can be used for contouring when fixed illumination angles are used, but ensuring that no other displacements are introduced in the process. When a tilt is introduced by object rotation, an important drawback is seen with this technique: the speckles gathered by the aperture of the interferometer imaging lens are shifted along the tilt direction, introducing and removing new speckle patterns in the aperture. The shift causes a sharp decrease in the contrast of the fringe patterns, known as speckle decorrelation. An alternative to object rotation is to rotate the illumination beams with respect to the static object [61], which produces similar results. It is also worth mentioning that moiré shadow techniques [82] bear a strong resemblance to the interferometric technique and can be used to understand the contouring effect.

Although this technique introduces moderate decorrelation, when temporal Fourier transform methods are used in the signal collected in each pixel, height measurement of objects ranging from a few hundreds of micrometers to a few tens of millimeters can be determined [83]. The phase obtained by rotating the object or tilting it for contouring can be gathered regardless of the kind of in-plane interferometer used, including those that have been recently developed [84]. Popular alternatives to the standard in-plane measurement along a single direction are radial in-plane setups that simultaneously detect multiple directions [85]. Another alternative is to use two wavelengths in this kind of interferometer for rotation measurement with in-plane sensitivity [86].

3.3 Shearography

A typical Michelson-type shearography setup [6,59,87–90] is presented in Fig. 3.5. As the illumination and observation configurations are the same as in the out-of-plane optical setup, the phase terms are similar, except that the observation direction $\theta_R \approx 0$ and depends on the tilt of the Michelson mirrors, which introduces shear in the image of the speckle patterns. The amount of shear is often assumed to be constant over the field of view, but it can vary over the object's surface if the object has a nonflat shape. As shear changes introduce evaluation errors that decrease the accuracy of the measurements [91], a quantitative evaluation of shear over the field of view [92] and the depth of field [93] is required for increased accuracy. The phase term is calculated again using Eq. (2.2), but now the approximate derivative of phase is expressed in the pose vector, as a collimated horizontal illumination is used:

Chapter 4

Illumination and Displacement Detection

4.1 Illumination Using Two Simultaneous Light Sources

To introduce the matrix notation for illumination changes, here we review and extend the notation used for the in-plane interferometer, where twin light sources were placed at the same distance from the origin, and along the negative and positive y axis. The optical path difference of Eq. (3.6) was expressed for the two light sources with subscripts (S), (R) and a pose after a matrix transformation such that the components u, v of displacement are detected by the in-plane interferometer. In our previous in-plane example of object rotation, our illumination geometry was determined by the vector difference $[\mathbf{r}_R - \mathbf{r}_{S'}] - [\mathbf{r}_R - \mathbf{r}_S] = (\sin\theta_{S'} + \sin\theta_S, 0, \cos\theta_{S'} - \cos\theta_S)$, which corresponds to our illumination-observation sensitivity, so Eq. (3.16) was obtained by the dot product of our illumination-observation sensitivity vector with the displacement components obtained after pose-rotation in γ, which in matrix notation, can be re-expressed as

$$k\begin{pmatrix} (\mathbf{r}_R - \mathbf{r}_S)\cdot\Theta_\gamma \\ 0 \\ 0 \end{pmatrix} = k\begin{pmatrix} \sin\theta_{S'} + \sin\theta_S & 0 & \cos\theta_{S'} - \cos\theta_S \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} \gamma y \\ 0 \\ -\gamma x \end{pmatrix}. \tag{4.1}$$

Using $\theta_S = \theta_R = \theta$, we obtained the optical path difference induced by rotation in Eq. (3.16) as $k\Lambda_\gamma = 2k\gamma y\sin\theta$. In general terms, to consider three sequential illuminations, we can re-express Eq. (4.1) as

$$\begin{pmatrix} \Lambda^{(1)} \\ \Lambda^{(2)} \\ \Lambda^{(3)} \end{pmatrix} = \begin{pmatrix} \Lambda_u^{(1)} & \Lambda_v^{(1)} & \Lambda_w^{(1)} \\ \Lambda_u^{(2)} & \Lambda_v^{(2)} & \Lambda_w^{(2)} \\ \Lambda_u^{(3)} & \Lambda_v^{(3)} & \Lambda_w^{(3)} \end{pmatrix}\Theta^T, \tag{4.2}$$

where the terms in the round brackets after the equal sign denote the illumination sensitivity effects, and the transpose of the pose vector Θ^T carries

Chapter 5

Transient Displacement Analysis

Whole-field displacement-detection techniques using electronic speckle pattern interferometry (ESPI) are reviewed in this chapter using pulsed and CW lasers for displacement measurement of fast, transient phenomena.* The capabilities of the leading optical setups used for speckle interferometry to study transient displacement events are discussed in terms of camera synchrony for the acquisition of the speckle patterns; these setups are compared with recently developed techniques.

Since 1978, considerable interest has been shown in the measurement of high-speed mechanical displacements using ESPI or TV holography [152–156]. Following the implementation of the first techniques, major improvements were brought by the development of pulsed lasers, and the applications of pulsed ESPI started to emerge [154,157,158]. Nowadays, the acquisition speeds achieved by electronic cameras are so high that they overcome the time sampling interval achieved with the old technology of pulsed lasers. As a consequence, CW lasers can be used with high-speed cameras [159]; if the light is not sufficient, micro-spheres can be used to enhance the reflectivity [160]. On the other hand, laser technology continues to evolve, and new types of pulsed lasers have been developed; in particular, ultrasound technologies have evolved to detect transient in-plane and out-of-plane displacements on the order of sub-nanometers [161].

The following sections first review the leading synchronization schemes [162] used to date when pulsed and CW laser illuminations are used for recording speckle patterns, and secondly they discuss the main setups that use this kind of synchrony.

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*For practical purposes in this book, a transient event is defined as a displacement that can be non-repeatable or repeatable, and which has a duration of less than 1/30 of a second, i.e., one TV frame time.

- The pulse phase delays control the synchronization of pulses with repeatable transient displacements: each pulse delay has been previously incremented to each frame repetition such that an appropriate sampling of the transient event is achieved.

As the phase can be extracted from a single speckle interferogram (or several) and a repetitive transient displacement can be obtained from mechanical strain experiments, a phase-delay synchrony can be produced in the laser pulses of each frame. The repetitive transient displacement represented schematically in Fig. 5.5(c) can be analyzed by sampling it with a pulse represented in part (b) that shifts the signal sampling at each frame due to a difference among the delayed pulses and the repetitive transient displacements. The laser pulse duration sets the main limitation of this method; for example, to obtain ten samples of a transient mechanical event with a laser pulse width of 20 ns spaced in time by 100 ns, the event would need to last 1 μs, achieving a maximum speed of 316 cm/s, which is one order of magnitude faster than the speed obtained by trying to capture a transient event with light pulses in each frame using a high-speed camera.

Either method 1 or 2 can make use of the the temporal-phase-unwrapping technique using single-shot phase maps with high-speed cameras in terms of the sampling intervals discussed in the two methods. However, sampling of a repetitive transient displacement using method 2 with the temporal-phase-unwrapping method would give similar time resolutions, also achieving the highest velocities of those two methods, especially if the laser pulse duration is short and the electronics allows the synchronization of short pulses with the repetitive transient displacement.

Although some lasers emit high-frequency pulses that are shorter than the camera interframe times, new laser technologies are necessary to get enough power from shorter pulses and single-frequency operation for ESPI transient event analysis. An alternative to using pulsed lasers is to use high-power CW lasers with short acquisition times in the camera. An example of temporal phase unwrapping without pulsed lasers allowed for the capture of events at 1 kHz [175].

Even though the use of a repetitive transient event with pulsed lasers allowed for an increase in the speed detection limit, the camera technology was still lagging at the onset of the implementation of these methods, and the technique of twin-pulse ESPI was suggested as an alternative.

5.3.3 Method 3: Twin pulses per two camera frames

The use of twin-pulse lasers provided some additional advantages for the application of ESPI in industrial environments [153]. The first double-pulse lasers used in ESPI were of the ruby type, which were Q-switched twice within one flash tube cycle to produce two laser pulses in a time interval between

Chapter 6

Phase Detection

Phase can be detected instantaneously using a single speckle pattern or using the time to gather a series of speckle patterns. The instantaneous approach, also called single-shot phase detection, gives a single speckle pattern in which a spatial carrier is embedded, but phase extraction from this kind of pattern is limited in bandwidth. More than one speckle pattern is needed to process the whole bandwidth and to extract phase values using phase-shifting procedures described in the literature [31,186]. The acquisition of more than one speckle pattern requires time, and time is related to the properties of the object under analysis, such as deformation or translation, and ambient thermal drifts. In theory, the object's properties must remain unchanged for each measurement, but in practice, they keep evolving for each measurement. Due to thermal and other noise effects in the acquisition process, the phase values are usually noisy and distorted, and smoothing procedures must be introduced in the numerator and denominator of the arctangent function that is always used in the final steps of phase extraction.

6.1 Carriers in Single-Shot Phase Detection

The carrier-fringe methods rely on a fringe pattern of known frequency that is later modified by a phase change, as was first suggested by Ichioka and Inuiya [187] in interferometric setups, and was later used in fringe projection systems, as shown in Fig. 6.1, where a typical fringe carrier is processed.

This example of the technique known as digital fringe projection [188] shows how the spatial carrier fringes created by projecting a consinusoidally varying intensity with a light projector over a plane surface shown in Fig. 6.1(a) are modulated by the height of a pyramidal object in Fig. 6.1(b). Only a single image of the fringe pattern is needed to obtain the phase if the frequency of the fringes is known as *a priori* information. Therefore, the departure from straight, vertical fringes conveys the phase information.

A sign-corrected phase map can be obtained if *a priori* knowledge is introduced in the fringe pattern. This knowledge can be expressed as a phase changes are averaged in an experiment. There have been similar developments, in which instead of four phase-steps, only three phase-steps can be produced [220]; other developments use Bayer filters [221], or even two phase-steps [222]. Speeds of 262,500 fps have been reported [223] for this kind of phase extraction procedure, and contouring has been achieved with similar techniques [224]. Advances in shearography have also reported spatial phase stepping using polarization arrays with CW lasers [225,226] and polarization arrays with pulsed lasers [227]. The new polarized sensors can now be found in commercial cameras; see, for example, Refs. [228,229].

6.5 Heterodyne Interferometry

The standard phase term of Eq. (1.6) contains a single phase term that shows an OPD that is proportional to the wavenumber k. However, in some experiments, it is possible to obtain phase terms with OPDs that are proportional to $\delta k = (k - k_0)$, where $\delta k \ll k$; this kind of interferometry is known as heterodyne. A simple interferometric setup to obtain this kind of phase term uses the standard out-of-plane interferometer setup with k_0 as a reference wavenumber. This is achieved by introducing an increment (or modulation) in wavelength by changing the current of a laser diode. Such an approach has been tested on specular and non-specular surfaces [230–232] such as $k - k_0 = -2\pi\delta\lambda/\lambda^2 = -k_0\delta\lambda/\lambda$, and the phase difference $\Delta\phi$ introduced by the wavenumber increment can be represented by

$$\Delta\phi = (k - k_0)\Lambda = \delta k\Lambda, \tag{6.18}$$

which can be approximated as

$$\Delta\phi \approx \frac{\partial k}{\partial\lambda}\delta\lambda\Lambda = -k_0\frac{\delta\lambda}{\lambda}\Lambda. \tag{6.19}$$

Similar phase terms but based on a reference grating wavenumber have been obtained in spectroscopic instruments (see, for example, Ref. [233]), or for measuring a differential phase with RMS better than 3 mrad [234]. Other options for heterodyning can be implemented using polarized heterodyne interferometry, Zeeman laser sources, or crystal components and acousto-optic modulators [235–239], or by translating a mirror, a glass wedge, or a diffraction grating [240]. Frequency multiplexing in time and space using heterodyne interferometry has also been proposed [241], as well as double heterodyne interferometry [242]. Simultaneous in-plane speckle measurements in two dimensions have been implemented by using an electro-optic modulator [243], and out-of-plane temporal measurements using $LiNbO_3$ for frequency heterodyning have been implemented in Ref. [237] and also in shearography [238].

Abundio Davila has been a researcher at the Centro de Investigaciones en Óptica (CIO) since 1986. He received a Bachelor of Science in Physics from the Physics Department of the Universidad Autónoma de Nuevo León (UANL), a Master of Science from the Applied Physics Department of the Centro de Investigación Científica y Educación Superior de Ensenada (CICESE), both in México, and a PhD from Loughborough University, UK, specializing in speckle interferometry techniques in 1992. Dr. Dávila has contributed to nondestructive optical testing techniques with pulsed and CW lasers and wavelength scanning interferometry and has contributed to spectrometry with tunable light sources. He was invited twice to collaborate as a Visiting Fellow and Visiting Research Associate at the Mechanical and Manufacturing Engineering Department of Loughborough University. He has given more than 42 conference presentations, holds 1 patent, and has written 40 journal articles with more than 570 citations.