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Review

Multi-colour microscopic interferometry for optical metrology and imaging applications

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ABSTRACT

Interferometry has been widely used for optical metrology and imaging applications because of their precision, reliability, and versatility. Although single-wavelength interferometery can provide high sensitivity and resolution, it has several drawbacks, namely, it fails to quantify large-discontinuities, large-deformations, and shape of unpolished surfaces. Multiple-wavelength techniques have been successfully used to overcome the drawbacks associated with single wavelength analysis. The use of colour CCD camera allows simultaneous acquisition of multiple interferograms. The advances in colour CCD cameras and image processing techniques have made the multi-colour interferometry a faster, simpler, and cost-effective tool for industrial applications. This article reviews the recent advances in multi-colour interferometric techniques and their demanding applications for characterization of micro-systems, non-destructive testing, and bio-imaging applications.

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1. Introduction

Interferometry has been widely used in research and development (R&D), and industrial applications because of its precision, reliability, and versatility. It is a well-established full-filed, non-contact, non-invasive optical tool which offers excellent sensitivity and resolution for metrology applications [1–3]. Interferometer has been used as an important investigating tool in the fields of fibre optics, optical metrology, surface profiling, microfluidics, mechanical stress/strain measurement, velocimetry, biology and medicine etc. [3–7]. Interferometric techniques can be used to inspect both reflecting (smooth) and scattering (diffusive) surfaces in wide range of sizes. The inspection can be done under static, quasi-static or dynamic conditions [8–10]. Conventional interferometry can only handle smooth (mirror like) samples. If the test surface is diffusive, the interference between reference and test beam results in no-visible fringe pattern. So, conventional interferometry fails to characterize samples with diffusive (speckled) surface. The interferometry that can study rough or scattering surfaces is known as Electronic/Digital speckle pattern interferometry (ESPI/DSPI) or TV holography (TVH) [8,11]. TV holography under microscopic configuration was demonstrated for characterization of shape, deformation, NDT on microsystems such as MEMS (Micro-Electro-Mechanical Systems) [2,4,12–15]. In conventional or speckle interferometry, the desired information about the object under study is encoded in the fringe pattern, which in fact represents the phase distribution.

The analysis of the interferogram produced by a test surface gives the parameters of interest relating to the surface. Several multiple-frame [1,16–18] and single-frame [19–24] methods have been reported for quantitative analysis of fringes. Temporal phase shifting, polarization phase shifting techniques etc. are popular multiple-frame methods. These methods can provide phase with high accuracy but cannot be used in dynamic situations and industrial measurement environment. Single-shot measurements where only a single frame or multiple frames in one go are recorded and analyzed for phase by an appropriate procedure have been reported. In recent years, numerous single-frame analysis methods such as Fast Fourier Transform (FFT) [25–27], Huang–Hilbert transformation (HHT) [26,28], Hilbert Transform (HT) [29–31], Pixelated-polarization phase shifting (PPPS) [20,32] etc. have been applied for single-interferogram analysis. Single (visible) wavelength measurements are accurate, but using single-wavelength greatly limits the wide spread applications of interferometry.

The major drawbacks associated with single wavelength fringe analysis are as follows: (i) for surface profiling of discontinuous surfaces, the unambiguous step-height measurement range is limited to half-a-wavelength ($\lambda/2$), (ii) for deformation measurement, it suffers from overcrowding of the fringes under relatively large loading conditions. The high frequency of the fringes sets a limitation due to speckle de-correlation for quantitative analysis, (iii) it cannot reveal the shape of a rough surface, (iv) it cannot resolve the discontinuities between polished and unpolished surfaces. The approaches adopted to overcome the problems associated with single-wavelength are based on scanning white light interferometry [33–35], spectrally resolved white light interferometry [36–39] and multiple-wavelength interferometry [17,40–46].

Scanning white light interferometry (WLI) is a state-of-the-art technique for measuring discontinuous surface profiles [33–35]. This makes use of the short coherence length of the white light source. High contrast fringe occurs only when the optical path difference (OPD) is close to zero. The 3-D plot of the axial positions of the zero OPD along the optical axis represents the surface profile of the object under test. Compared to single wavelength phase shifting interferometry, the scanning white light interferometry is rather slow, as the number of frames to be recorded and evaluated is large [33–35]. The spectrally resolved white light interferometry (SRWLI) is a variation of WLI in which the white light interferogram output of WLI is spectrally resolved into its constituent colour interferograms [36–39]. All the colour interferograms are analyzed for respective phases, which are then used to determine the profile. The phases at all the wavelengths can be evaluated by phase shifting technique. However this procedure gives only a line profile of the object, although the requirement on number of frames is similar to the single wavelength phase shifting interferometry.

In multiple-wavelength techniques more than one visible (e.g. red (R), green (G), and blue (B)) laser wavelengths are used for measurements. Each wavelength will generate its own interference pattern which contains the desired information of the object. The acquisition of the multiple-wavelength interferograms can be done in the following two different ways: (i) sequential illumination mode [17,47] in which interferograms are recorded with different wavelength one after another sequentially. This is a time consuming process, and (ii) simultaneous illumination mode [48–51] in which all the interferograms are recorded in one go by using a RGB CCD camera. This approach makes the fringe acquisition as simple as in single-wavelength case. Following three different approaches have been used for 3-colour recording: (a) Bayer filter 1-CCD sensor [52–55], (b) 3-CCD sensor [24,49,52,56], and (c) Foveon X3 sensor [46,52,57]. We will discuss these three strategies for simultaneous recording of 3-colours in Section 4.

The Bayer filter 1-CCD RGB camera has been demonstrated for surface profiling of large discontinuities [23,51,58,59], and simultaneous measurement of shape and deformation [23,48], non-destructive testing (NDT) of large defects [60], simultaneous acquisition of blood flow, blood volume, and oxygenation on human fingers using dual-wavelength laser imaging [61] etc. Recently, white light illumination combined with 1-CCD RGB camera was successfully demonstrated for surface profiling of micro-lens array and large-discontinuities [30], biological cells such as human Red-Blood-Cell (RBCs) [21,50,62], onion skin/cells [22], fish-eye cornea [55] etc. This approach was further simplified by using single-shot methods instead of multiple-frame methods for phase measurements [21,23,24].

The 3-CCD RGB camera has been demonstrated for surface profiling of large discontinuities using RGB laser interferometry [49,63,64], analysis of aerodynamic flow using a three-colour differential interferometry [44], simultaneous measurement of in-plane and out-of-plane displacement derivatives using RG speckle interferometry [65], 3D displacement measurement by two-wavelength (RB) simultaneous DSPI and DSP (Digital speckle photography) [66]. The 3-CCD camera was also combined with white light scanning interferometry for surface profiling of microstructures [49,63,64]. The 3-CCD can provide high-resolution imaging, but they are expensive.

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