Optics Communications 285 (2012) 5029–5036

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Optical surface profile measurement using phase retrieval by tuning the illumination wavelength

Peng Bao*, Giancarlo Pedrini, Wolfgang Osten

Institut für Technische Optik, Universität Stuttgart, Pfaffenwaldring 9, 70569 Stuttgart, Germany

ARTICLE INFO

Article history:
Received 13 June 2012
Received in revised form
3 August 2012
Accepted 4 August 2012
Available online 23 August 2012

Keywords:
Metrology
Surface measurements
Figure
Phase retrieval
Image reconstruction techniques
Holography

ABSTRACT

In this paper, we present a method for measuring the surface profile of an object by using diffraction intensity patterns recorded at different illumination wavelengths. The main advantages of this technique are: simple optical set-up, high immunity to noise and environmental disturbance, since no reference beam (like in holography) or additional moving parts are needed. Two iterative calculations are synchronously performed using two sequences of diffraction intensity patterns, producing fast convergence to the expected result. The effects of different parameters on the accuracy and efficiency of the method are investigated. Simulation and experimental results are presented.

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1. Introduction

Optical full field methods are well suited for the measurement of object shapes [1,2] and several techniques, such as grating or fringe projection [3,4], low coherence interferometry [5,6] and wavelength-scanning interferometry [7], have been proposed for determining the profile of large (some square meters) and microscopic structures. Digital holography, which became feasible along with the development of electronic recording devices (CCDs and CMOS), has been widely applied for the investigation of technical objects and biological samples [8,9] and some setups based on this technique have been used for measuring the surface profile and for quality control. Phase-shifting digital holography allows high accuracy in the reconstruction of three-dimensional objects [10,11]. By using a coherent mask produced by a spatial light modulator, the shapes of test objects can be remotely compared with a master object by the holographic technique [12,13]. However, conventional digital holography requires a reference beam and this can be a limitation. In particular when the source has low temporal coherence (e.g. excimer laser), a tedious and sometimes cumbersome process of optimizing the path length between object and reference beams is necessary. Beside the coherence requirements, attention has to be paid to the robustness of the set-up with respect to external influences such as vibrations and air turbulences.

A lot of effort has been directed to make interferometrical methods insensitive to environmental influences and investigations have been made with the purpose to reconstruct amplitude and phase without using reference beams and thus avoiding the disadvantages described above [14–17]. In this case, a pixelated detector is used to record different intensities of diffraction patterns while some experimental parameters are changed; the phase distribution is then recovered by iterative processing the recorded intensities. To acquire enough intensities of diffraction patterns, some techniques were used, such as moving an aperture inside the wavefront to record a sequence of intensities from different parts of the object [18], displacing the recording camera to record intensities at different planes [19,20] and moving a phase mask to record different modulated intensities [21]. These arrangements require the use of external mechanical moving devices (e.g. for displacing the aperture, the phase mask or the camera) and are thus sensitive to the environmental disturbance. A deformable mirror can be used to avoid the requirements of moving devices [22]. By using a designed periphery, the transmission test object can be reconstructed from one intensity measurement [23]. The phase retrieval techniques using multiple illumination wavelengths has an extended measurement range and does not require external moving devices [24,25].

Here we present a method where two iteration calculations are synchronously performed using two sequences of diffraction intensity patterns recorded at different wavelengths. This technique has fast convergence speed and high accuracy.

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* Corresponding author.
E-mail address: itobaope@ito.uni-stuttgart.de (P. Bao).

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http://dx.doi.org/10.1016/j.optcom.2012.08.018

2. Set-up and algorithms

2.1. Experimental set-up

Fig. 1 shows the set-up used for the investigations. The beam emitted by a tunable laser is at first coupled into a fiber. The light at the fiber output is collimated (plane wave) and illuminates the object. An aperture in front of test sample limits the measurement area and a camera, located at the distance Z from the object, records a set of diffraction intensities obtained by changing the illumination wavelength. Fig. 1 shows an in-line setup for probing transmitting sample. For the investigation of reflecting objects, a beam splitter should be introduced between the collimator and the test object, and the camera should be placed after the beam splitter.

Fig. 2 shows the relation between the surface profile and the optical phase of a test object. We assume transparent objects made of isotropic material. For the sake of simplicity we consider the one-dimensional case where the profile is described by a continuous function $\Delta h(s)$ (Fig. 2a), by sampling $\Delta h(s)$ at intervals Δs (Fig. 2b) we get an array $\Delta h(l\Delta s)$, which is used to approximate the profile of the test surface. l is an integer number and in the following treatment we will simply denote the profile at $l\Delta s$ by $\Delta h(x)$. When the object is illuminated by a plane wave having wavelength λ, the phase change due to the object is

$$\Delta\phi(x)=\frac{2\Delta\pi h(x)}{\lambda}(n_{obj}-n_{air}) \tag{1}$$

where, n_{obj} and n_{air} are the refractive index of the material from which the object is made and air, respectively. For reflecting objects, the relation between phase and object profile is

$$\Delta\phi(x)=-\frac{4\Delta\pi h(x)}{\lambda} \tag{2}$$

Here the illumination beam goes though the optical path twice and the highest position of the surface has the lowest phase delay. According to Eqs. (1–2), the phase distribution is proportional to the surface profile and inversely proportional to the illumination wavelength. Notice that in the cases of transparent objects the dispersion of the test material should be considered and compensated.

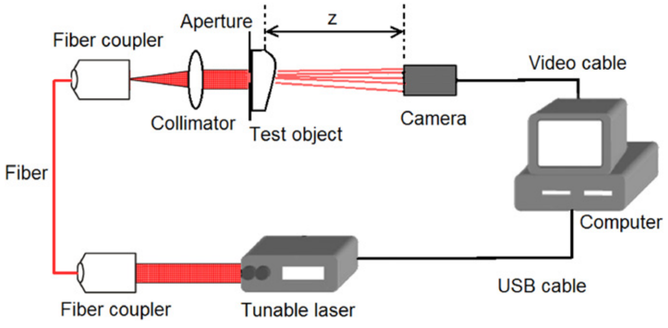

Fig. 1. Schematic of the measurement system.

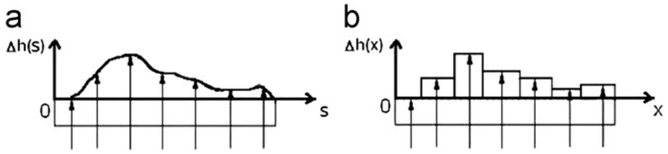

Fig. 2. Physical model of a transparent object (one dimensional): continuous curve (a) and discrete array (b).

2.2. Limitations of the phase retrieval method using single sequence intensity patterns (PRSS)

The PRSS methods can be used to get a wrapped phase and after application of an unwrapping procedure the object profile can be obtained [24,25]. However, the phase cannot be unwrapped until the iteration is completed. The relation between the wrapped phases ϕ_k and unwrapped phases ϕ_{unw_k} is

$$\phi_k(x',y')=\phi_{unw\_k}(x',y')+N(x',y')2\pi \quad N(x',y')=0,\pm 1,\pm 2\ldots \tag{3}$$

where the subscript k indicates the illumination wavelength λ_k. The process for retrieving the phase is shown in Fig. 3 [24,25]. The relation between the phases and the wavelengths is

$$\begin{aligned}\phi_{k+a}(x',y')&=\frac{\lambda_k}{\lambda_{k+a}}\phi_k(x',y')=\frac{\lambda_k}{\lambda_{k+a}}\phi_{unw\_k}(x',y')+\frac{\lambda_k}{\lambda_{k+a}}N(x',y')2\pi\\&=\frac{\lambda_k}{\lambda_{k+a}}\phi_{unw\_k}(x',y')+\left|\frac{\lambda_k}{\lambda_{k+a}}-1\right|N(x',y')2\pi+N(x',y')2\pi\end{aligned} \tag{4}$$

Here the indicator "a" is 1 or -1 and is used to keep the value of k valid: when $k+a>K$, the value of a is changed to -1; when $k+a<1$, the value of a is changed to 1.

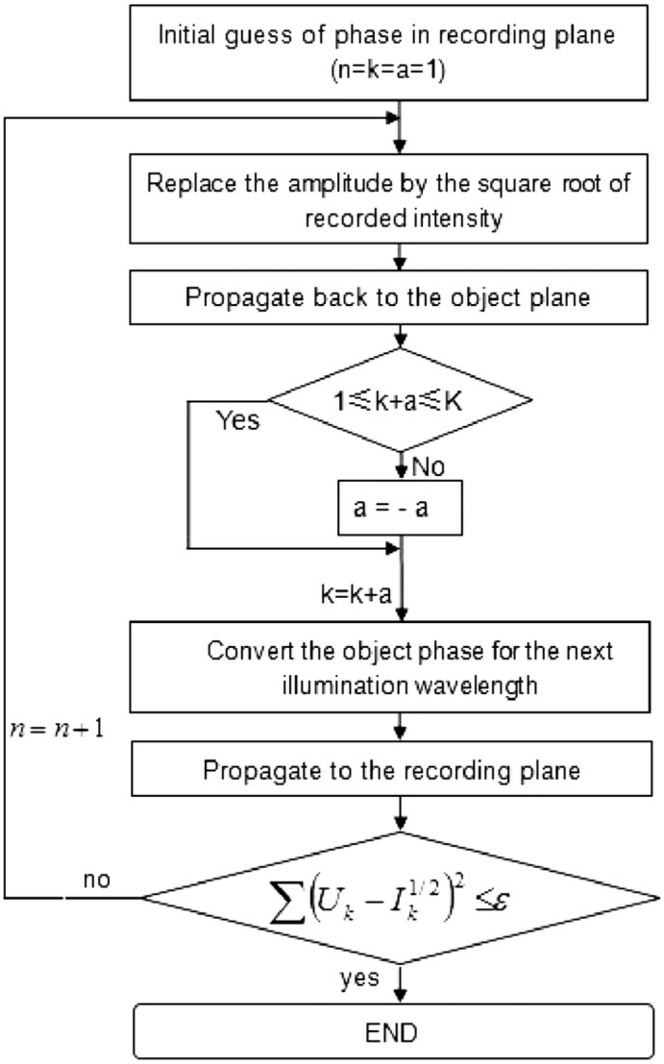

Fig. 3. Flowchart of the PRSS: n is the iteration number; k is the serial number of the used illumination wavelength; I_k is the recorded intensity; U_k is the calculated amplitude; a is the indicator; K is the total number of recorded intensities.

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