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Color deflectometry for phase retrieval using phase-shifting methods

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ABSTRACT

In this paper, we propose a technique based on a color fringe pattern used on deflectometry experiment. The advantages of using color fringe patterns together with phase shifting techniques on deflectometry experiment are presented. An experimental wavefront reconstruction of a progressive lens shows the accuracy and simplicity of these techniques used to process the deflection measurements.

1. Introduction

Techniques based on non-contacting measurements are valuable tools in many industrial fields because they can provide highly sensitive examination of extended phase objects with high resolution and deliver fast rate data acquisition. These techniques are widely recognized as promising in areas such as medicine, on-line inspection, reverse engineering and computer-aided design or manufacturing [1].

One of the simplest and most powerful methods to measure the emerging wavefront from a phase object is deflectometry. The local slopes of the surface are optically measured and then the surface itself is reconstructed using an integration procedure. Traditionally, these measurements are made using moiré deflectometry and Ronchi and Hartmann test [2]; however, most of these methods require coherent illumination and accuracy alignment of the optical setup. With recent advances in computer technology, the experimental setup has become very simple and easier to use in wavefront measurement applications: sketch of the experimental setup is shown in Fig. 1 and consists of a TFT (thin film transistor) monitor to generate the fringe patterns and a CCD camera to capture them [3,4]. This approach has found several practical applications mainly due to its simplicity of operation [5,6]. One important aspect is the processing of the fringe patterns. This is especially true because for each wavefront reconstruction it is necessary to analyze at least two deflectograms with different orientations. Typically, Fourier-based techniques are used to process the acquired images because every orientation results on a single fringe pattern [7–10]. However, the Fourier-based demodulation methods could produce erroneous results if the spatial variations of the amplitude or the phase are larger than the carrier frequency [11,12].

In this paper we present a phase-shifting technique based on a color fringe pattern used on deflectometry experiment. The key point of the proposed procedure is to display a color fringe pattern, which are formed by three phase-shifted sinusoidal fringe patterns, codified in red, green, and blue color channels, respectively. In the next section, we describe in some detail our proposal for deflection maps measurement by the use of several images captured using color deflectometry. In Section 3, experimental results are presented. Finally, in Section 4 we present the conclusions.

2. Principle of measurement and information processing

2.1. Principles of the measurement

Suppose that one has a fringe pattern printed (or displayed in a LCD) across the plane (x, y), with fringes along the y-direction. If we place a pure phase object in front of the fringe pattern, the phase object changes the optical path lengths traveled by light rays through it. If the phase is inhomogeneous in the x-direction, the rays will be deflected by [3,13]

$$\alpha \approx \frac{\partial \phi_{\boldsymbol{x}}}{\partial x},$$

where $\boldsymbol{x} = (x, y)$, and $\phi_{\boldsymbol{x}}$ is the optical path length accumulated by a ray traveling through the phase object at the position $\boldsymbol{x}$. Let the distance from the test object to the pattern displayed on the screen be defined as d, then the fringes will appear shifted in the x-

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direction a distance (see Fig. 1)

$$\alpha d \approx d\frac{\partial \phi_{\boldsymbol{x}}}{\partial x}. \tag{1}$$

In general case, a fringe pattern captured by the camera is described by

$$I_{\boldsymbol{x}} = a_{\boldsymbol{x}} + b_{\boldsymbol{x}} \cos\left(\frac{2\pi}{p}(\boldsymbol{x}\cdot\boldsymbol{v} + d\nabla\phi_{\boldsymbol{x}}\cdot\boldsymbol{v})\right), \tag{2}$$

where $a_{\boldsymbol{x}}$ is the background illumination, $b_{\boldsymbol{x}}$ is the amplitude modulation, $\boldsymbol{v} = (\cos\varphi, \sin\varphi)$ is the normal direction vector of the pattern displayed on the screen, the term $\nabla\phi_{\boldsymbol{x}} = (\partial\phi_{\boldsymbol{x}}/\partial x, \partial\phi_{\boldsymbol{x}}/\partial y)$ is the wavefront gradient, and p is the pattern period. The term $(2\pi/p)\boldsymbol{x}\cdot\boldsymbol{v}$ represents the carrier frequency of the acquired fringe pattern, and the term $(2\pi/p)\,d\nabla\phi_{\boldsymbol{x}}\cdot\boldsymbol{v}$ is the directional derivative of the wavefront multiplied by the sensitivity of the measurement setup.

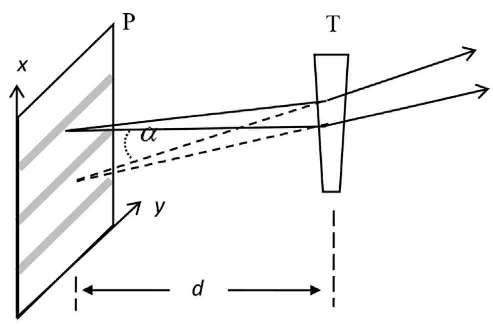

Fig. 1. One-dimensional deflectometry: P is a displayed fringe pattern, and T is a pure phase object.

The resultant measurement of this setup is the directional derivative of the wavefront $\phi_{\boldsymbol{x}}$ oriented in the direction of $\boldsymbol{v}$. A common procedure to estimate the wavefront ϕ is to acquire two or more directional derivatives and integrate them [10,14,15]. Typically, Fourier-based techniques are used to process every acquired image because every directional derivative results on a single fringe pattern [7–10]. However, these demodulation techniques have two important drawbacks: (1) the computational effort employed to process all the acquired images is large; and (2) these techniques are prone to errors particularly if the spatial variations of the amplitude or the phase are larger than the carrier frequency; in this situation, the spectral information will be overlapping [11,12].

2.2. Color phase-shifting technique

Let us consider a color fringe pattern displayed on a screen. This color fringe pattern is formed by three phase-shifted sinusoidal fringe patterns, in the red, green, and blue channels [16,17]; the intensities of these fringe patterns are defined as

$$I_{\boldsymbol{x}}^R = I_{\boldsymbol{x}}' + I_{\boldsymbol{x}}'' \cos(\psi_{\boldsymbol{x}} - \theta),$$
$$I_{\boldsymbol{x}}^G = I_{\boldsymbol{x}}' + I_{\boldsymbol{x}}'' \cos(\psi_{\boldsymbol{x}}),$$
$$I_{\boldsymbol{x}}^B = I_{\boldsymbol{x}}' + I_{\boldsymbol{x}}'' \cos(\psi_{\boldsymbol{x}} + \theta), \tag{3}$$

where $I_{\boldsymbol{x}}^R$, $I_{\boldsymbol{x}}^G$, and $I_{\boldsymbol{x}}^B$ are the intensities of each pixel in the red, green, and blue channels, respectively; $I_{\boldsymbol{x}}'$ is the average intensity, $I_{\boldsymbol{x}}''$ is the intensity modulation, θ is the phase displacement of the fringe patterns chosen in such way to help to reduce errors due to

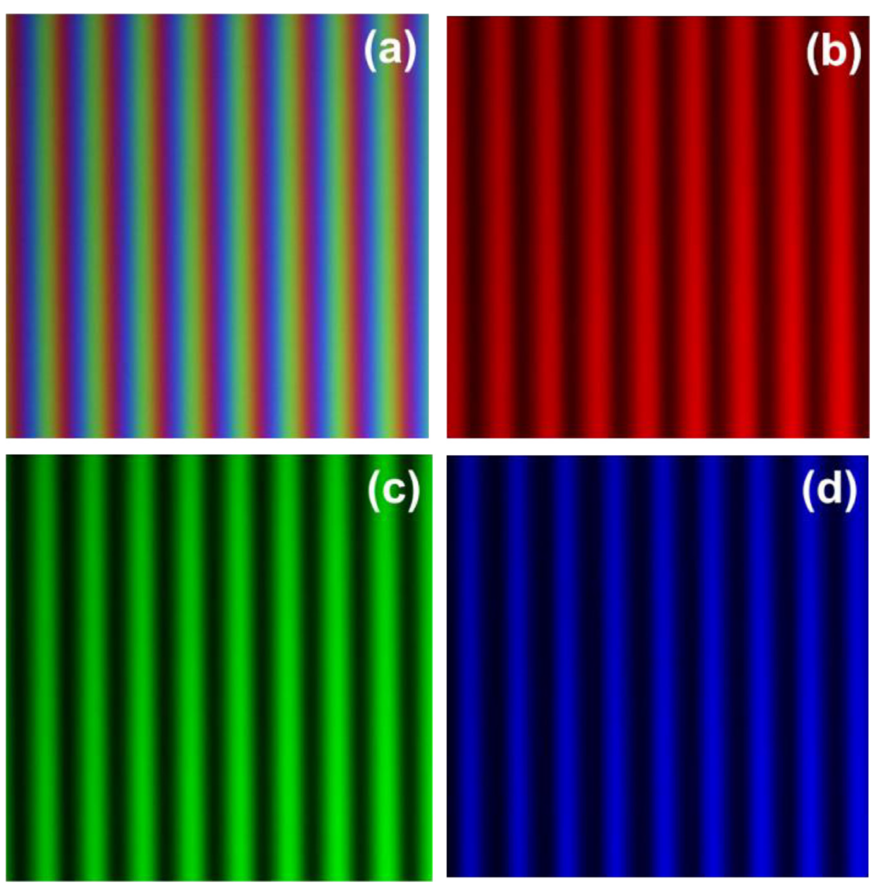

Fig. 2. (a) Color fringe pattern and (b)–(d) sinusoidal phase-shifted fringe patterns corresponding to Eq. (3). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)