Optics Communications 282 (2009) 2800–2805

Contents lists available at ScienceDirect

Optics Communications

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

Quantitative detection and compensation of phase-shifting error in two-step phase-shifting digital holography

W. Chen, C. Quan *, C.J. Tay, Y. Fu

Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore

ARTICLE INFO

Article history:
Received 9 January 2009
Received in revised form 14 April 2009
Accepted 14 April 2009

PACS:
42.25.Hz
42.30.Kq
42.40.−i
42.40.Lx
42.87.Bg

Keywords:
Phase-shifting digital holography
Phase-shifting error
Quantitative detection
Quantitative compensation

ABSTRACT

Phase-shifting digital holographic technique is a powerful tool for the measurement of various physical parameters, such as object deformation and liquid or cell's refractive index change. However, for an accurate measurement, phase-shifting error in the reference wave path is still a major issue. In this paper, three novel and simple algorithms are proposed to quantitatively detect and correct phase-shifting error for a pure phase object in two-step phase-shifting digital holography. Influence of phase-shifting error is illustrated, and the effectiveness of the proposed algorithms is demonstrated by numerical simulation results.

1. Introduction

Since holography was introduced by Gabor [1], it has been widely applied to practical measurements [2–6]. Some types of techniques, such as off-axis digital holography [7] and phase-shifting digital holography [8,9], have also been developed. Compared with wet chemical processing method in optical holography, off-axis digital holography is limited by the lower resolution of charge-coupled device (CCD), and object size cannot be too large. In the off-axis experimental arrangement, some algorithms, such as convolution method [7] and Hilbert transform [10], can be employed to obtain phase-contrast maps. Phase-shifting digital holography can overcome the above problems, and enhance the quality of reconstructed images [8,9]. Phase-shifting technique [11,12] usually employs two or more fringe patterns to extract phase-contrast maps, and has been widely applied to many fields [7,12]. However, with a phase-shifting operation, phase-shifting error in the reference wave path can not be completely avoided due to an imperfect calibration of a piezoelectric transducer. The phase-shifting error can make a reconstructed image blurred, especially for the reconstructed phase-contrast map. To eliminate the influence of phase-shifting error, some algorithms, such as frequency-shifting method [13] and an averaging method [14], have been developed. In the previous approaches [13,14], much more experimental effort should be made to eliminate or suppress phase-shifting error. In Ref. [15], amplitude deviation summation of the reconstructed wave is calculated as an evaluation function to determine phase-shifting error.

In this paper, we propose three novel and simple algorithms to quantitatively detect and correct phase-shifting errors for a pure phase object in two-step phase-shifting digital holography. Influence of the phase-shifting errors is illustrated, and the effectiveness of the proposed approaches is demonstrated by numerical simulations.

2. Theoretical analysis

The in-line hologram intensities, denoted by $I_i(x,y)$, are obtained by the interference between an object wave $O(x,y;z)$ and a plane reference wave $R_i(x,y)$ in the hologram plane.

$$I_i(x,y) = O(x,y;z)O^*(x,y;z) + R_i(x,y)R_i^*(x,y) + R_i(x,y)O^*(x,y;z) + R_i^*(x,y)O(x,y;z), \quad (1)$$

* Corresponding author. Tel.: +65 6516 8089; fax: +65 6779 1459.
E-mail address: mpeqcg@nus.edu.sg (C. Quan).

0030-4018/$ - see front matter
doi:10.1016/j.optcom.2009.04.025

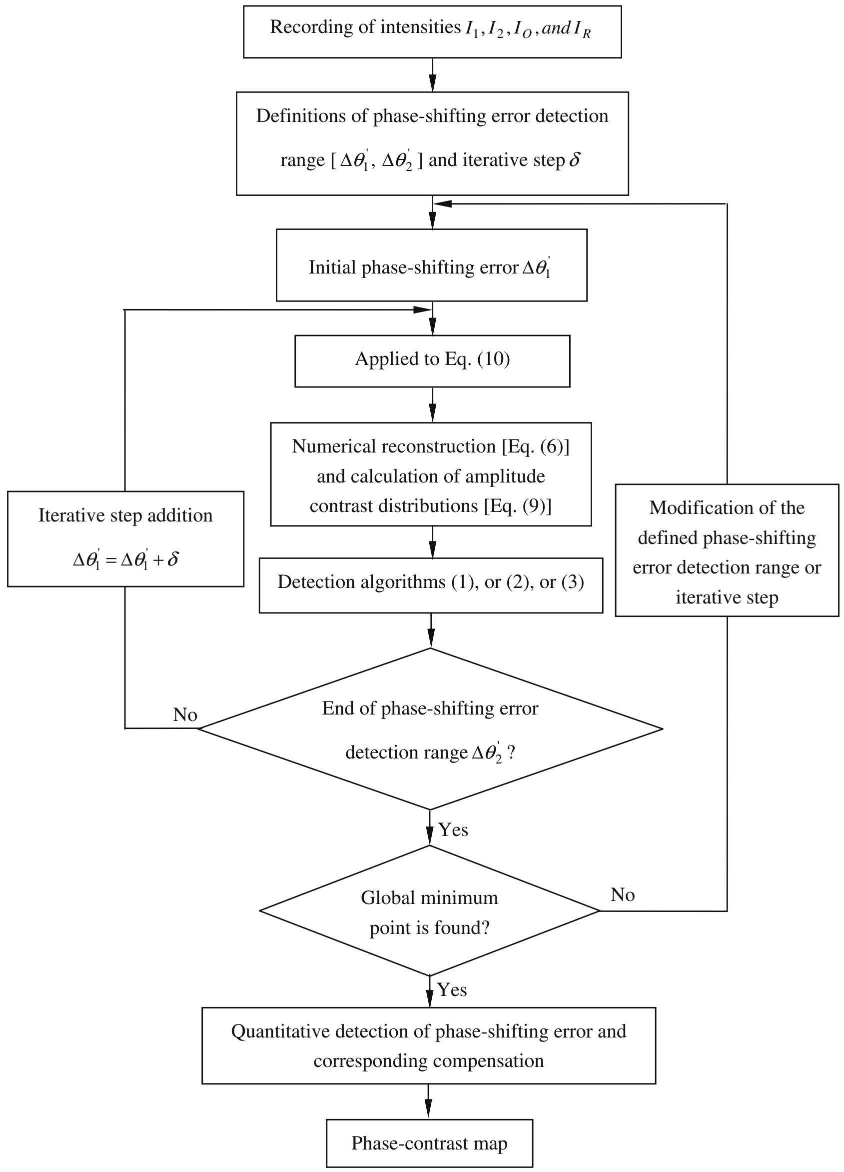

Fig. 1. A flow chart of the procedure to determine phase-shifting error using the proposed algorithms.

where z denotes the distance between object plane and hologram plane, factor $i = 1, 2$, and * denotes the complex conjugate.

Without phase-shifting error, the object wave in the hologram plane is expressed as

$$O(x,y;z) = \frac{I_1(x,y) - I_O(x,y) - I_R(x,y) + j[I_2(x,y) - I_O(x,y) - I_R(x,y)]}{2R} = A(x,y)\exp[j\varphi(x,y)], \tag{2}$$

where R denotes real amplitude of the reference wave, $A(x,y)$ denotes real amplitude of the object wave, $\varphi(x,y)$ denotes phase map of the object wave, $j = \sqrt{-1}, I_O = |A|^2,$ and $I_R = |R|^2$. The intensities $I_1(x,y)$ and $I_2(x,y)$ are recorded when the phase shift of reference wave path is 0 and $\pi/2$, respectively. In practice, $I_O(x,y)$ and $I_R(x,y)$ can be recorded by blocking the reference and object waves, respectively.

With a phase-shifting error of $\Delta\theta$ in the reference wave path, $I_1(x,y)$ and $I_2(x,y)$ are described by

$$I_1 = R^2 + A^2 + RA\exp(j\varphi) + RA\exp(-j\varphi), \tag{3}$$

$$I_2 = R^2 + A^2 - jRA\exp(j\varphi)\exp(-j\Delta\theta) + jRA\exp(-j\varphi)\exp(j\Delta\theta), \tag{4}$$

where for simplicity, the coordinate (x,y) is omitted. Hence, the object wave in the hologram plane is given by

$$O(x,y;z) = \frac{I_1 - I_O - I_R + j(I_2 - I_O - I_R)}{2R} = \frac{1}{2}[1 + \exp(-j\Delta\theta)]A\exp(j\varphi) + \frac{1}{2}[1 - \exp(j\Delta\theta)]A\exp(-j\varphi), \tag{5}$$

After the object wave is determined in the hologram plane, an object wave $O(\xi,\eta;0)$ in the image plane is determined by

$$O(\xi,\eta;0) = F^{-1}[H(f_x,f_y;-z)O(f_x,f_y;z)], \tag{6}$$

where f_x and f_y are spatial frequencies, F^{-1} denotes 2D inverse Fourier transform, $O(f_x,f_y;z)$ denotes 2D Fourier transform of $O(x,y;z)$, and $H(f_x,f_y;-z)$ is a transfer function described by