Optics & Laser Technology 74 (2015) 103–107

Contents lists available at ScienceDirect

Optics & Laser Technology

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

An improved windowed Fourier transform filter algorithm

Ran Zhao, Xinglong Li, Ping Sun *

College of Physics and Electronics, Shandong Normal University, Jinan 250014, China

ARTICLE INFO

Article history:
Received 5 May 2015
Received in revised form
23 May 2015
Accepted 4 June 2015
Available online 11 June 2015

Keywords:
Image processing
ESPI
Windowed Fourier transform
Fringe analysis

ABSTRACT

In order to reduce the speckle noise in fringe patterns obtained by Electric Speckle Pattern Interferometry (ESPI), an improved windowed Fourier transform filter algorithm was proposed. The amplitude maximum of the fringe frequency scanned across a given window is set as the filtering criterion, which the optimum frequency image is obtained and the threshold window is not set in the window Fourier filter algorithm. The proposed algorithm is used to filter the fringe patterns obtained by ESPI. Experiment results show that the proposed algorithm has a better performance in reducing the speckle noise and has a high precision in phase calculation. The proposed algorithm can be used to filter other image as a low-pass filter.

1. Introduction

Electronic speckle pattern interferometry (ESPI) [1] is a highly accurate measurement technique which has been widely used in three dimensional (3-D) shape measurement, deformation measurement, vibration analysis and nondestructive testing, with some attractive characteristics such as whole-field measurement, real-time observation of a fringe pattern, high-speed and non-contact measurement of a micro deformation. Since directly observed output in ESPI is the interference fringe patterns by which the measured object deformation can be determined roughly, various methods to obtain the whole-field phase distribution of a deformed object quantitatively from the interference patterns have emerged including phase-shifting techniques [2–4] and carrier technique with Fourier transform [5]. However, due to the inherent noises in speckle fringe pattern, it is hard to extract the phase accurately. It is necessary, therefore, to filter the speckle fringe pattern for further image processing in precise phase measurement.

In general, the traditional filtering methods can mainly be classified into spatial filters and spectral filters. Although the spatial filters such as mean filter [6] and median filter [7] can smooth the noise of image effectively, at the same time, lots of image texture details and edge information are lost. Whereas spectral filters are different methods which convert the image from spatial domain into frequency domain by Fourier transform and the image is filtered by suppressing or increasing the spectral components selectively, such as the Butterworth filter [8]. Further, other effective filters, such as spin filter [9], adaptive filter [10] and partial differential equations filter [11], are proposed when the direction of the fringes is considered. It is useful to filter by the windowed Fourier transform filter [12,13], which select a window to be processed in spectrum by a window functions to isolate from adjacent areas. With the windowed Fourier filter a filtering threshold is required to be set in advance. The signals of which amplitude in spectrum is smaller than the threshold are filtered out as noises, whereas those amplitudes greater than threshold are retained. The threshold selected, therefore, has a great influence on image filtering. However, it is quite time-consuming to search a proper threshold and difficult to determine an optimal threshold for an image.

In this paper we present a new filtering method, which does not need to set a threshold in advance. By searching for the peak of the amplitude in a small region of the spectrum, the maximum amplitude of the region is obtained and regarded as a filtering criterion at the local area, rather than simply compared with a given filtering threshold. The operation of the new filtering is simple compared with the window Fourier filter, then can be found a broader range of applications.

* Corresponding author.
E-mail address: SunPingmail@163.com (P. Sun).

http://dx.doi.org/10.1016/j.optlastec.2015.06.005

2. Principle of windowed Fourier transform filter

The Window Fourier Transform (WFT) and the Inverse Window Fourier Transform (IWFT) of $f(x, y)$ at a given point $x = \mu, y = \nu$ can be expressed as [13]

$$Sf(\mu, \nu; \xi, \eta) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(x, y)g(x-\mu, y-\nu)\exp(-j\xi x - j\eta y)dxdy \tag{1}$$

$$f(x, y) = \frac{1}{4\pi^2}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} Sf(\mu, \nu; \xi, \eta)g(x-\mu, y-\nu)\exp(j\xi x + j\eta y)d\mu d\nu d\xi d\eta \tag{2}$$

where $f(x, y)$ is a two dimensional image, $Sf(\mu, \nu, \xi, \eta)$ is the four dimensional WFT spectrum of $f(x, y)$, (x, y) and (μ, ν) are spatial coordinates and (ξ, η) is the frequency coordinate at each pixel. $g(x, y)$ denotes a window function, which differ from conventional Fourier transform, can be chosen as a Gaussian function, $g(x, y) = \frac{1}{\sqrt{\pi\sigma_x\sigma_y}}\exp(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2})$, where σ_x and σ_y are the standard deviations of the Gaussian function in x and y directions respectively. For the Gaussian window function, a WFT basis $h(x, y; \xi, \eta)$ is introduced and defined as

$$h(\mu, \nu; \xi, \eta) = g(x, y)\exp(j\xi x + j\eta y) \tag{3}$$

Therefore, the WFT filter operation of $f(x, y)$ by utilizing $h(x, y; \xi, \eta)$ can be expressed as

$$Sf_m(\mu, \nu; \xi, \eta) = 0 \quad \text{if } f(x, y) \otimes h^*(x, y; \xi, \eta) < Thr \tag{4}$$

$$Sf_m(\mu, \nu; \xi, \eta) = f(x, y) \otimes h^*(x, y; \xi, \eta) \quad \text{if } f(x, y) \otimes h^*(x, y; \xi, \eta) \geq Thr \tag{5}$$

where Thr represents a preset threshold and $Sf_m(\mu, \nu; \xi, \eta)$ is the threshold spectrum of $f(x, y)$ at the spacial point (μ, ν). The filtered fringe pattern $f'(x, y)$ can be expressed as

$$f`(x, y) = \frac{1}{4\pi^2}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{a}^{b}\int_{c}^{d} Sf_m(\mu, \nu; \xi, \eta) \otimes h(x, y; \xi, \eta)d\xi d\eta d\mu d\nu \tag{6}$$

where the symbols * and $\otimes$ denote the conjugate and convolution operations, which are implemented with respect to the variables x, y. Note that the integration limits are set from a to b and from c to d for ξ and η, instead of from $-\infty$ to $+\infty$, namely the size of integral window for the frequency (ξ, η) is set as $[a, b] \times [c, d](b > a > 0, c > d > 0)$. The values of a, b, c and d can be estimated from the fringe pattern and the integral window should contain at least one fringe width [14]. For convenience of calculations, we select the size of integral window is $w_x \times w_y$ and set $w_y = 2w_x$ along the direction of fringe pattern. Since the intensity distribution with the Gaussian function is most concentrated in the region $4\sigma_x \times 4\sigma_y$ around the zero point, we chose $\sigma_x = \omega_x/4$, $\sigma_y = \omega_y/4$ to get a better result. Assume that the WFT spectrum of random noises which uniformly distribute in the fringe pattern has different frequency components with small spectrum coefficients [11]. Thus the spectrum of which amplitude around the peak of the window function is retained, whereas the others are filtered out as noise and the filtered fringe pattern $f'(x, y)$ is obtained.

3. Principle of non-threshold windowed Fourier transform (NTWFT) filter

A fringe pattern can be generally expressed as [4]

$$I(x, y) = a(x, y) + b(x, y)\cos[\varphi(x, y)] + n(x, y) \tag{7}$$

where $I(x,y)$ is the recorded intensity, $a(x,y)$ and $b(x,y)$ represent the background intensity and the amplitude modulation at a point (x,y) respectively, and $n(x,y)$ noises. $\varphi(x, y)$ is the phase distribution caused by the deformation of the tested object. Eq. (7) can be rewritten as

$$I(x, y) = a(x, y) + n(x, y) + \frac{1}{2}b(x, y)\exp[j\varphi(x, y)] + \{\frac{1}{2}b(x, y)\exp[j\varphi(x, y)]\}^* \tag{8}$$

where the symbol * denotes the complex conjugate. Note that the fringe pattern consists of four parts, two exponential terms, a background term and a noise term. For convenience, the WFT is applied to the two exponential functions in Eq. (8) at the special point $x = \mu$, $y = \nu$ and the results can be expressed as [13]

$$B(\mu, \nu; \xi, \eta) = \frac{1}{2}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} b(x, y)\exp\{j[\varphi(x, y)\}g(x-\mu, y-\nu)exp(-j\xi x - j\eta y)dxdy \tag{9}$$

$$B^*(\mu, \nu; \xi, \eta) = \frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} b(x, y)\exp\{-j[\varphi(x, y)\}g(x-\mu, y-\nu)\exp(j\xi x + j\eta y)dxdy \tag{10}$$

where $B(\mu, \nu; \xi, \eta)$ and $B(\mu, \nu; \xi, \eta)^*$ are the WFT spectrum of $\frac{1}{2}b(x, y)\exp[j\varphi(x, y)]$ and $\{\frac{1}{2}b(x, y)\exp[j\varphi(x, y)]\}^*$, respectively. Assume that the fringe modulation in the local area around (μ, ν) is the same, i.e.,$b(x, y) = b(\mu, \nu)$, and the phase is linear. Subsequently, we expand the phase distribution $\varphi(x, y)$ in a Taylor series and the first order approximation of $\varphi(x, y)$ is given by

$$\varphi(x, y) = \varphi(\mu, \nu) + \varphi_x(\mu, \nu)(x-\mu) + \varphi_y(\mu, \nu)(y-\nu) \tag{11}$$

where $\varphi_x(\mu, \nu)$ and $\varphi_y(\mu, \nu)$ are the phase differential of $\varphi(x, y)$ in the x and y directions respectively, i.e., the local frequencies. Let us define $x - \mu = t$, $y - \nu = l$ and Eqs. (9) and (10) can be rewritten as

$$B(\mu, \nu; \xi, \eta) = \frac{1}{2}b(\mu, \nu)\exp\{j[\varphi(\mu, \nu) - \xi\mu - \nu\eta]\}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} g(t, l)\exp\{-j[\xi - \varphi_x(\mu, \nu)]\}\exp\{-j[\eta - \varphi_y(\mu, \nu)]\}tldtdl \tag{12}$$

$$B^*(\mu, \nu; \xi, \eta) = \frac{1}{2}b(\mu, \nu)\exp\{-j[\varphi(\mu, \nu) - \xi\mu - \nu\eta]\}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} g(t, l)\exp\{j[\xi - \varphi_x(\mu, \nu)]\}\exp\{j[\eta - \varphi_y(\mu, \nu)]\}tldtdl \tag{13}$$

With the Gaussian function $g(x,y)$, Eqs. (12) and (13) can be expressed as

$$B(\mu, \nu; \xi, \eta) = \frac{1}{2}b(\mu, \nu)\exp\{j[\varphi(\mu, \nu) - \xi\mu - \eta\nu]\}G[\xi - \varphi_x(\mu, \nu), \eta - \varphi_y(\mu, \nu)] \tag{14}$$