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Normalization and noise-reduction algorithm for fringe patterns

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Abstract

This paper presents a fringe pattern normalization and noise-reduction algorithm. Locally the background noise is suppressed, the modulation normalized and the noise smoothed. An expression to calculate the cosine-only term is formulated. It is related to the directional derivatives of the intensity fringes. Two-dimensional Fourier series are used to calculate the parameters needed for the algorithm. Experimental work is presented using diffraction and ESPI images. The programming is relatively simple and involves mainly local convolutions. The processing time using a 2 GHz computer to normalize an image of 256×256 pixels is approximately one second.

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1. Introduction

The use of light to analyze problems like stresses, cracks, deformations, topography, etc. involves the use of optical methods such as photoelasticity, interferometry, diffraction, moiré, ESPI, synthetic-aperture-radar [1,2], etc. In general, by using the above methods we obtain fringe patterns that have a phase function which contains the desired information.

There are many methods to achieve the phase from the fringes. The most popular methods probably are those which use phase shifting (PS) [3] or fast Fourier transforms (FFT) with carrier [4] or without carrier [5]. The PS methods need various images and the FFT generally have an ambiguity on the resulting phase when closed fringes are analyzed. The method explained in Ref. [5] uses half-plane Fourier filtering to deduce the phase from single fringe patterns that includes closed fringes. By applying the cosine function to the resulting phase map a normalized and smoothed fringe pattern is obtained. However, if the fringes are speckled, to obtain acceptable smoothing it requires the design of pass-band filters which does not always produce the best results, in particular for low-period fringes. An improvement of the above method can be found in Ref. [6], but again, it may distort the low-period fringes and the areas where no fringes are present act like distortion sources. There are some phenomena which are difficult to obtain fringes satisfying the conditions needed to apply the PS and FFT methods, for example transient phenomena and vibration analysis [7]. In general, we can say that an ideal fringe analysis method is relatively easy to program, it needs only one image, and calculates the phase quickly and accurately. Unfortunately, no such method exists currently. What the current fringe analysis methods have in common is that the calculated phase is more accurate if the fringes under analysis are noiseless and well contrasted. Furthermore, there are methods that require normalized fringes to obtain good results [8].

There are FFT methods to normalize sinusoidal fringes, for example, using a filter in the frequencies domain [9] or a quadrature operator using 1D Reisz filters [10]. However, these methods cannot smooth adequately the speckle

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fringes noise, in which case additional smoothing techniques should be used after the normalization procedure. Other methods find the peaks and valleys of the fringes and use their coordinates to design filters, but they need good quality skeletons [11]. In Ref. [12] is described an algorithm to obtain smooth and normalized fringes generated by speckle-pattern interferometry according to the fringe intensity slope and the distance ratio to neighboring skeletons. The skeleton is calculated and manipulated using the fringes slopes map. So, the success of the method depends on the correct calculation of the skeletons. Unfortunately, the method described to find such skeletons, when closed fringes appear, requires the slopes map again to determine some spurious lines due to fringes slope changes. This is not an easy task and may require user intervention in some cases. Another method was proposed to improve the signal-noise ratio in the interferograms by using adapted algorithms for temporal and local filtering [13]. The purpose is to extract the skeletons of fringes to classify flaws. A division of the interferogram by and estimated background intensity was enough for shading correction. However, it is difficult to determine thresholds suitable for the entire image. Some other methods utilize iterative procedures requiring high programming amount and processing time [14–16].

In this paper we describe a method to filter the noise and normalize the fringe patterns simultaneously. This procedure is done locally allowing the normalization of non-sinusoidal fringe patterns. We formulate an expression to calculate the cosine profile of the fringes without the background noise and the modulation terms. This expression contains terms involving only directional derivatives of the intensity fringe pattern. During our research, we found that the best derivative direction is that which is normal to the fringes orientation. All the parameters needed by the algorithm are calculated from the coefficients of a two-dimensional Fourier series. The proposed algorithm was tested using simulated and experimental fringe patterns. The simulated fringes have sinusoidal and Bessel profiles. The experimental fringes were obtained from diffraction and ESPI configurations of time-averaged vibration and out-of-plane deformations.

In the following sections we will describe the proposed algorithm; the results obtained using experimental and simulated images, and the conclusions of the article.

2. Theoretical analysis of noise reduction and normalization

2.1. General algorithm

Let $I(x,y)$ be the intensity of a discrete fringe pattern having a cosine, Bessel or another profile function. We will also assume that inside a rectangular window W of dimensions KL can be expressed by a cosine term such as the following:

$$I(x_1,y_1) = A(x_1,y_1) + B(x_1,y_1)\cos[\varphi(x_1,y_1)], \tag{1}$$

where (x_1,y_1) are the pixels of W in local Cartesians coordinates, $\varphi(x_1,y_1)$ is the phase that determines the fringes geometry, $A(x_1,y_1)$ and $B(x_1,y_1)$ are the background and modulation terms, respectively. We use the pixel intensities in the window to calculate some Fourier coefficients at its center ($x_1 = 0$, $y_1 = 0$), i.e. at (x,y) on the global coordinates. By shifting the window we obtain these coefficients for each pixel (x,y) on the full image.

Assuming that inside the window W, $A(x_1,y_1)$ and $B(x_1,y_1)$ are constants and the phase $\varphi(x_1,y_1)$ is a plane, (which implies that $\varphi_x(x_1,y_1)$ and $\varphi_y(x_1,y_1)$ are both constants) we can do the following operations

$$\begin{aligned} p_1(x,y) &= I_x(x,y)\cos(\alpha) + I_y(x,y)\sin(\alpha),\\ p_2(x,y) &= I_{xx}(x,y)\cos^2(\alpha) + 2I_{xy}(x,y)\cos(\alpha)\sin(\alpha)\\ &\quad + I_{yy}(x,y)\sin^2(\alpha)\\ p_3(x,y) &= I_{xxx}(x,y)\cos^3(\alpha) + 3I_{xxy}(x,y)\cos^2(\alpha)\sin(\alpha)\\ &\quad + 3I_{xyy}(x,y)\cos(\alpha)\sin^2(\alpha)\\ &\quad + I_{yyy}(x,y)\sin^3(\alpha), \end{aligned} \tag{2}$$

where the subscripted symbols mean derivation of $I(x,y)$ along the x or y the times indicated, for example I_{xy} mean $\partial^2 I/\partial x\,\partial y$, and $\alpha(x,y)$ is a derivative direction function given by the user, to obtain

$$\begin{aligned} p_1(x,y) &= -B[\varphi_x\cos(\alpha) + \varphi_y\sin(\alpha)]\sin(\varphi),\\ p_2(x,y) &= -B[\varphi_x\cos(\alpha) + \varphi_y\sin(\alpha)]^2\cos(\varphi)\\ p_3(x,y) &= B[\varphi_x\cos(\alpha) + \varphi_y\sin(\alpha)]^3\sin(\varphi), \end{aligned} \tag{3}$$

where the sub-index of p were set according to the powers of the directional derivatives. This last equation can be manipulated to obtain the cosine term without the background and the modulation function

$$\cos[\varphi(x,y)] = -p_2(x,y)\Big/\sqrt{p_2^2(x,y) - p_1(x,y)p_3(x,y)}. \tag{4}$$

Notice that $p_1(x,y)$, $p_2(x,y)$ and $p_3(x,y)$ (Eq. (2)) depend only on the values that can be calculated from Eq. (1), i.e. $\alpha(x,y)$ and derivatives of $I(x,y)$. At first glance, an expression to calculate the cosine term can be obtained without using the derivative direction $\alpha(x,y)$, however, if it is not introduced, the normalization algorithm becomes dependent on the fringes geometry. Notice that the root term in Eq. (4) vanishes when $\alpha(x,y)$ is perpendicular to the gradient direction, that is, when $\mathrm{tg}[\alpha(x,y)] = -\varphi_x(x,y)/\varphi_y(x,y) \approx -I_x(x,y)/I_y(x,y)$; however, as we will see later, we choose $\alpha(x,y)$ along the gradient direction, therefore in theory the denominator does not vanish.

It is known that the derivative operator is noise sensitive and that most of the fringe patterns have noise. Therefore it is essential to formulate a robust procedure to reduce its effects on the derivatives calculation. In the following section, we will explain a method to calculate the derivatives of the fringes and the proper values for $\alpha(x,y)$ based on the fringes orientation calculation.