International Journal of Signal Processing, Image Processing and Pattern Recognition
Vol.6, No.6 (2013), pp.101-108
http://dx.doi.org/10.14257/ijsip.2013.6.6.10

Numerical Investigation of Phase Estimation for 3D Measurement in the Fringe Projection Technology

Mohammed Bailich[1], Mustapha Bahich[2], Benaissa Bellach[1] and Mohammed Rahmoun[1]

[1]*Equipe d'électronique et télécommunications, École Nationale des Sciences Appliquées, Université Mohammed Premier, Oujda, Morocco*
[2]*Laboratoire d'ingénierie et matériaux, Faculté des sciences Ben Msik, Université Hassan II Mohammedia, Casablanca, Morocco*

mbailich@gmail.com, mbahich@gmail.com

Abstract

Phase data modulating the intensity of fringe patters can provide useful information about object surface or shape using an optical fringe projection system. Measuring the phase map of recorded fringe pattern via an appropriate phase retrieval algorithm can lead as to the object shape information. Several physical and numerical parameters can affect the estimation of phase maps. We systematically studied effects of theses parameters on different phase analyses using a recently proposed directional wavelet algorithm (DWA) that is based on 2D continuous wavelet transform (2D-CWT), an advanced multiscale decomposition algorithm. We considered two types of parameters that are often presented in recorded intensity images: local spatial frequencies of data and modulation rate of fringe patterns. In this paper, we propose a study of the phase retrieval problem by comparing two different methods on numerical and experimental data, to improve the performance of the analysis process and then the accuracy of results.

Keywords: *Non destructive testing, Surface inspection, Fringe projection technique, Phase measurement, Wavelet transform.*

1. Introduction

In recent years, fringe projection technique is gradually involved in many scientific and industrial fields. This is becoming a trend due to some key features, including non destructivity, efficiency, high accuracy, reliability and adaptation to the industrial environment requirements. Generally, the phase coding the projected fringe pattern on an object is related to its shape. Then, measuring the phase leads to the 3D object profile. The phase retrieval in optical metrology is very important process for many industrial applications [1].

Many phase retrieval algorithms have been conceived which differ in the adopted approach such as Fourier transform method [2], phase shifting [3], direct phase detection and wavelet transform method [4]. The wavelet transform and other space frequency or space scale approaches are now considered standard tools by researchers in signal processing, and many applications have been proposed that point out the interest of these techniques [5]. In optical metrology and, more precisely, fringe pattern analysis, wavelets are currently in operational software. Two-dimensional continuous wavelet transform (2D-CWT) techniques have been used successfully to demodulate fringe patterns and retrieve the phase even when the

ISSN: 2005-4254 IJSIP
Copyright ⓒ 2013 SERSC

recording process is accompanied by the presence of noise [6]. In this paper we propose the use of the 2D-CWT algorithm to demodulate fringe patterns and the study of some environmental parameters effects on the accuracy of results. In the following section, the fringe pattern technique is introduced. The background theory of the 2D-CWT fringe pattern demodulation algorithm is discussed in Section 3. Computer-generated and real fringe patterns are used to test and discuss the effects of previously mentioned parameters on the phase retrieval algorithm reliability, and we conclude in Sections 4 and 5 respectively.

2. Fringe Projection Technique

The fringe projection is an optical metrology technique that offers a topographic description of an illuminated surface (the object of test).

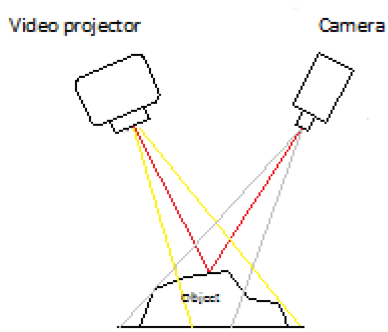


Figure 1. Fringe Projection Principle

This technique is based on the projection of a rectilinear fringes network from a video projector on the studied surface (or the object) which its distortions appear as a modification of the fringes orientation in the x &y axis [7]. This modification results from a variation of the phase distribution that is directly related to the object distortions:

$$\phi(x,y)=\frac{2\pi}{p}\tan(\theta).z(x,y) \tag{1}$$

Where ϕ is the phase, p is the interfringe, z is the distortion of interest and θ is the angle the CCD camera and the video projector.

Therefore, to determine the z distortion we should retrieve first the phase distribution that codes the projected fringe pattern. There are many algorithm that can be used to demodulate fringe patterns, such as Fourier transform based algorithm, phase stepping, digital phase locked loop, direct phase detection and wavelet transform based method [8].

3. Directional Wavelet Phase Measurement

Generally the intensity of a fringe pattern can be expressed as follows:

$$I(x,y)=I_0[1+V\cos(my+\phi(x,y))] \tag{2}$$

 Copyright ⓒ 2013 SERSC

Where I_0, V and m are the average intensity, the fringe visibility and the modulation rate respectively.

$\phi(x, y)$ is the phase of fringe pattern and x&y are the simple indices for the x and y axis respectively.

A fringe pattern tends to resemble to non-stationary signals. This motivates researchers to investigate wavelet transform as a time-frequency technique for fringe pattern demodulation problem. The wavelet transform can detect the local characteristics of signals and obtain a time–frequency description of it [9].

A wavelet is an oscillating function with a compact width and a zero mean. Figure 2 shows the 2D version of usual mother wavelet that called Mexican hat.

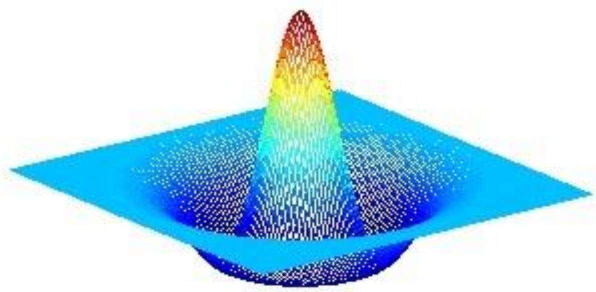


Figure 2. 2D Mexican Hat Wavelet

A family of 2D analyzing wavelets (*i.e.*, directional wavelets) are generated by translating the mother wavelet via the location parameter $\vec{\xi} \in R^2$, dilating it with the scale parameter s>0 and rotating it by the angle α. It can be expressed as [10]:

$$\psi_{s,\vec{\xi},\alpha} = \frac{1}{s}\psi\left(R^{-\alpha}\frac{\vec{x}-\vec{\xi}}{s} \right) \tag{3}$$

$R^{-\alpha}$ designates the rotation matrix by the angle α

$$R^{-\alpha} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \tag{4}$$

The 2D-CWT of a two-dimensional signal f is given by:

$$W_f\left(s,\vec{\xi},\alpha\right) = \iint_{R^2} f(\vec{x})\frac{1}{s}\psi^*\left(R^{-\alpha}\frac{\vec{x}-\vec{\xi}}{s} \right) d\vec{x} \tag{5}$$

Where $\vec{\xi} \in R^2, s > 0, \alpha \in [0,2\pi]$

In 2D-CWT, the fringe pattern $f(x, y)$ is projected onto the wavelets $\psi_{s,\vec{\xi},\alpha}$ basis and the resulted wavelet coefficients $W_f\left(s,\vec{\xi},\alpha\right)$ reach their maximal value when the two dimensional analyzing wavelet and the fringe pattern are locally more similar and their frequencies are very close.

Copyright ⓒ 2013 SERSC

To demodulate a fringe pattern, its wavelet transform is first calculated. Then, the ridge of the wavelet coefficients array $\mathrm{W}(s,\alpha)$ for each pixel in the fringe pattern with the coordinates $\vec{\xi}$ is detected and its corresponding coefficient argument will be taken as the pixel phase:

$$\mathrm{ridge}(\vec{\xi}) = |\mathrm{W}(s_m, \vec{\xi}, \alpha_m)| = \max(|\mathrm{W}(s, \vec{\xi}, \alpha)|) \tag{6}$$

$$\phi(\vec{\xi}) = arctg\left(\frac{\mathrm{Im}(W(s_m, \vec{\xi}, \alpha_m))}{\mathrm{Re}(W(s_m, \vec{\xi}, \alpha_m))}\right) \tag{7}$$

Where s_m and α_m are the scale and rotation angle corresponding to ridge value.

4. Simulated and Experimental Results

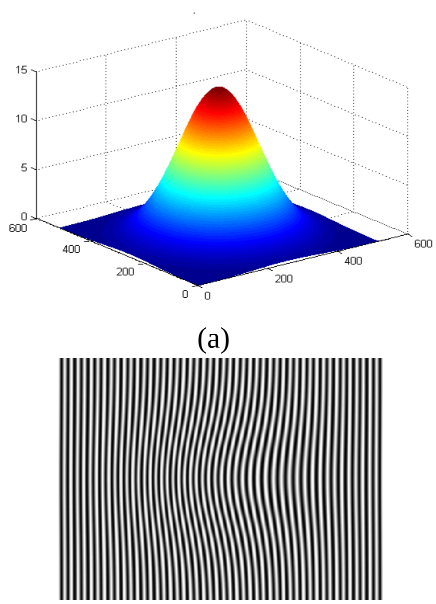
A numerical simulation of phase retrieval employed in fringe projection application has been performed. First, a computer generated phase that is shown in Figure 3-a and is described by the following equation is generated.

$$\phi(x,y) = \beta \exp\left(-0.00006\left[(x-256)^2 + (y-256)^2\right]\right) \tag{8}$$

The resultant modulated fringe pattern by the phase distribution is shown in Figure 3-b and given by the equation

$$I(x,y) = 1 + 0.5\cos(my + \phi(x,y)) \tag{9}$$

With modulation rate m set to 0.6 radian/pixel.



(a)

(b)

Figure 3. (a) A Computer-Generated Object, (b) Its Corresponding Fringe Pattern

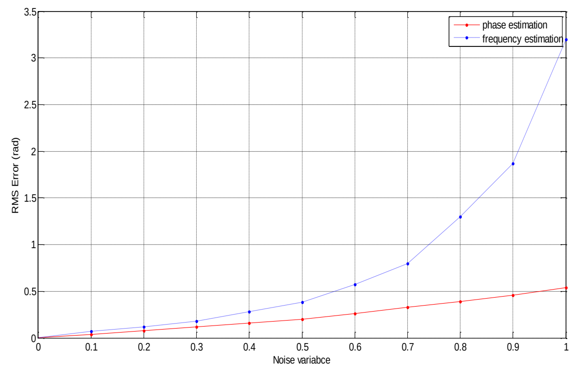
Copyright ⓒ 2013 SERSC

The particular situation modeled was the used CCD camera has 512 x 512 for resolution with the pixel dimension is 7.4 x 7.4 µm.

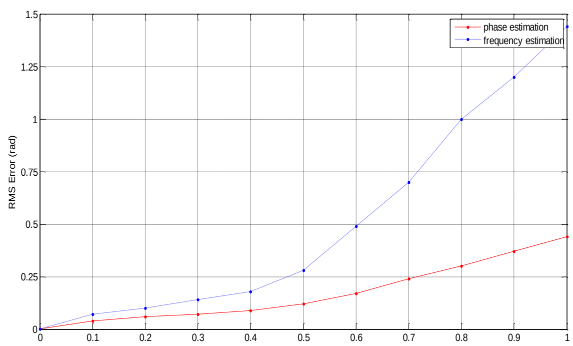
There are different noise types in real world. Multiplicative noise is common beside additive noise. Multiplicative noise, that is naturally dependent on the image data, is multiplied by (not added to) the original image. In this study, the multiplicative noise that will be used is the known as speckle noise.

To analyze the noise immunity of the wavelet analysis algorithm, we apply it to several examples of the previous fringe pattern with both additive and multiplicative increasing Gaussian noise levels.

The Figure 4-a presents, in the case of additive noise, the plots of RMS (Root mean square) errors of the estimated phase distributions with the noise variance for the both frequency and phase based algorithms. The Figure 4-b presents the obtained RMSE results in the multiplicative noise case.



(a)



(b)

Figure. 4 RMS Errors Versus Noise Variance. (A) Additive Noise, (B) Multiplicative Noise

The analysis of these results shows clearly that the phase based wavelet analysis algorithm gives the best values of the phase distribution with less error values. This is certainly due to the fact that the phase distribution is slowly variable and it presents small spatial frequencies values that are very affected by noise and especially in the presence of multiplicative one.

Figure 5 shows the effect of the modulation rate [11] of the projected fringe pattern via the RMS error of accuracy of retrieved phase map. The RMS deviation of the measured phase,

Copyright ⓒ 2013 SERSC

for 4 different β values, increases with the object spatial frequency increment β. The purpose of this part is the analysis of the effect of the high spatial frequencies variance of the surface object. It can be seen that RMS error goes on reducing as the object surface is slowly variant giving an excellent agreement between the theoretical and the obtained results.

Moreover, the RMS error is considerably high when the modulation rate is less than the maximum spatial frequencies. When the modulation rate is higher than 1 rad/pixel, the obtained RMS error is constant as can be seen from Figure 6 and has an average of 0.1 rad. The phase recovery will remain accurate if a spatial carrier is added so as to remove the deformation sign ambiguity, and at the same time, to reduce the noise effect.

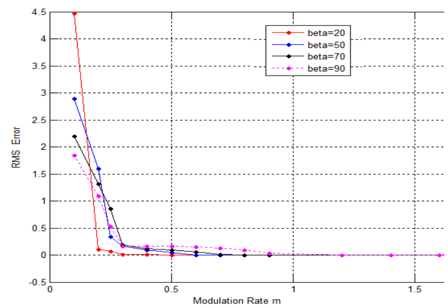


Figure 5. RMS Error versus Modulation Rate (for 4 maximal spatial variation values)

In order to confirm the validity of the directional wavelet phase retrieval method, a real specimen was used to extract the phase and then measure the object height profile (Figure 6). To obtain the height variation of reference plane and the carrier frequency of the projected fringes in the image plane, the CCD camera was focused to the center of the projected fringe pattern and then reference image was stored to camera's memory as RGB image. After this, the specimen was put on the reference plane and object image stored into the camera as shown in Figure 7. These stored two images later downloaded to computer for analysis.

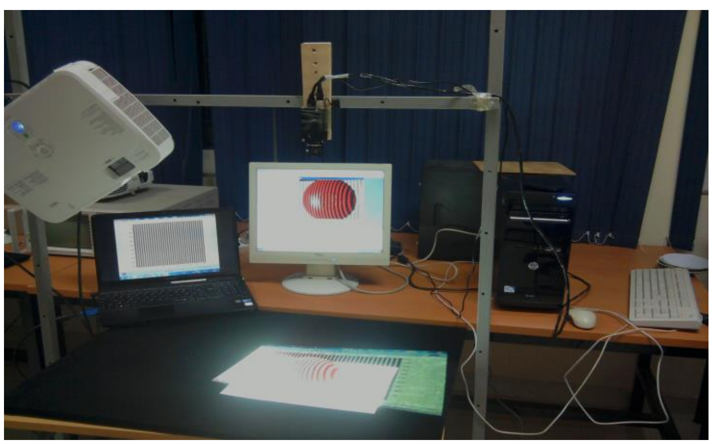


Figure 6. The Fringe Projection Set-up

 Copyright ⓒ 2013 SERSC

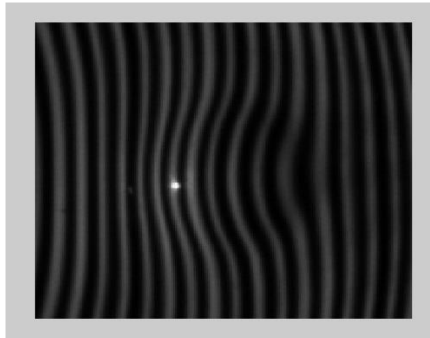


Figure 7. Projected Sinusoidal Fringes on the Specimen

The procedure outlined above was used to extract the phase from the real image that is shown in Figure 7. The 2D continuous wavelet transform of reference image and object image were first calculated in the Matlab environment. The wrapped phase of the reference fringe image and object fringe image were calculated from their complex values and an appropriate unwrapping procedure was used to correct discontinuities in the wrapped phases. Finally phase distribution of object is calculated by subtracting the carrier using the reference phase and the height distribution of the object that was calculated using experimental parameters is shown in Figure 8.

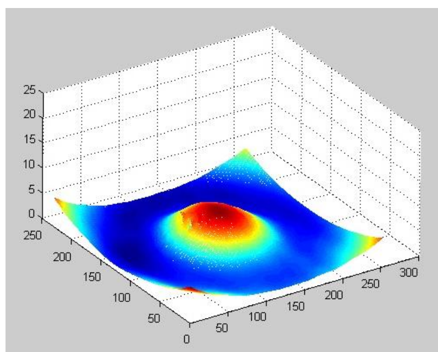


Figure 8. 3D Height Profile of the Specimen

5. Conclusion

In this paper, we present the surface estimation using fringe projection technique where the phase is retrieved from a single recorded image using a directional wavelet transform demodulation algorithm while the experimental set-up remains simple (which is one of the general advantages of the fringe projection technique, simple experimental set-ups). The use of a single fringe pattern to retrieve the phase is an important feature of this technique, because it allows the real time measurement and control of dynamic phenomena such as deformation.

We have also studied effect of several parameters, such as the noise, the spatial variation of the surface and the modulation rate, on the performance of the phase retrieval algorithms and we have presented an analysis of the obtained errors of the resultant phase distributions.

In conclusion, both simulation and physical experiments show that the directional wavelet based fringe analysis algorithm is able to provide surface height measurements with a better reliability using one single fringe pattern that can easily be recorded by the detection system.

Copyright ⓒ 2013 SERSC

As a future work, we tend to investigate more directional transforms for fringe pattern processing and metrological problems solutions that can be implemented as a surface inspection tool in different industrial manufacturing and maintenance process.

Acknowledgements

The authors want to show gratitude to the reviewers for their helpful comments and suggestions.

References

[1] J. R. Fienup, “Phase-Retrieval Algorithms for a Complicated Optical System”, Appl. Opt., vol. 32, **(1993)**, pp. 1737-1746.
[2] M. Takeda, H. Ina and S. Kobayashi, “Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry”, JOSA, vol. 72, **(1982)**, pp. 156-160.
[3] S. Zhan and S. T. Yau, “High-resolution, real time 3D absolute cordinate measurement based on phase-shifting method”, Opt. Express, vol. 14, **(2006)**, pp. 2644-2649.
[4] M. Afifi, A. Fassi-Fihri, M. Marjane, K. Nassim, M. Sidki and S. Rachafi, “Paul wavelet-based algorithm for optical phase distribution evaluation”, Optics Comm., vol. 211, **(2002)**, pp. 47-51.
[5] C. Torrence and G. P. Compo, “A practical guide to wavelet analysis”, Bulletin. American Meteo. Soc., vol. 79, **(2002)**, pp. 61-78.
[6] M. Bahich, M. Bailich, A Imloul, M Afifi and E. M. Barj, “A comparative study of one and two-dimensional wavelet-based techniques for noisy fringe patterns analysis”, Opt. Comm., vol. 290, **(2013)**, pp. 43-48.
[7] M. A. Sutton, W. Zhao, S. R. McNeill, H. W. Schreier and Y. J. Chao, “Development and Assessment of a Single-image Fringe Projection Method for Dynamic Applications”, Experimental Mechanics, vol. 41, pp. 205-217 (2001).
[8] T. Yoshizawa, “Handbook of Optical Metrology: Principles and Applications”, CRC Press, **(2009)**.
[9] Q. Kemao, H. S. Seah and A. Asundi, “Wavelets in optical metrology”, Persp. Eng. Optics., **(2003)**, pp. 117-133.
[10] J.-P. Antoine and R. Murenzi, “Two-dimensional directional wavelets and the scale-angle representation”, Signal Proc., vol. 52, **(1996)**, pp. 259-281.
[11] M. Bahich, M. Afifi and E. M. Barj, A numerical spatial carrier for single fringe pattern analysis algorithm, Optik., vol. 122, **(2011)**, pp. 1821-1824.

 Copyright ⓒ 2013 SERSC