Chapter 37
Assessment of Fringe Pattern Normalisation for Twelve Fringe Photoelasticity

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Abstract Single colour image based photoelastic techniques have gained importance in the recent years. In twelve fringe photoelasticity (TFP) technique, the whole field fringe order (N) data is obtained by comparing RGB intensities of all the pixels in the image with that in the calibration table. This technique is suitable for problems where multiple acquisitions of the model are difficult. Initially, the methods were proposed to demodulate a maximum fringe order of 3 since the colours tend to merge after this. There have been efforts to push this limit by using advanced imaging hardware and fluorescent light sources. Recent research in this field explored the use of fringe pattern normalisation in conjunction with the use of theoretically generated calibration table for isochromatics modulation. However, the method was demonstrated using models having almost uniform fringe gradients. This work assesses the performance of fringe pattern normalisation for twelve fringe photoelasticity in problems having different fringe gradients. Studies are carried out in the benchmark problem of a circular disc under diametral compression. The isochromatic results obtained are compared with the corresponding values obtained analytically.

Keywords Twelve fringe photoelasticity • Fringe pattern normalisation • Image processing • RGB photoelasticity • Isochromatics

37.1 Introduction

Photoelasticity is a whole field technique which gives direct information about principal stress difference and their orientations. Over the years, several digital methods have been proposed for whole field determination of isochromatic data [1]. Among these, Twelve Fringe Photoelasticity (TFP) has gained importance as they require only a single colour image for whole field isochromatics demodulation [2–4]. In this technique, the fringe orders are estimated based on the colour components in the isochromatic image. The modelling of the intensity variation of the output image depends on many parameters such as transmission response of the components in the polariscope, spectral composition of the light source, quarter-wave plate error, dispersion of the stress-optic coefficient and the spectral response of the camera [2]. Since accurate consideration of all these parameters is difficult, in practise, a method based on calibration table and color matching is followed [1–4]. The technique is useful especially in problems involving time-varying phenomena and industrial problems where one does not have the luxury to acquire multiple images.

Determination of isochromatic data using TFP is performed in three steps i.e., calibration, fringe order estimation by colour difference formula and its refinement by invoking fringe order continuity. The total fringe order at a point of interest in the model is obtained by comparing the colour components at the point of interest with that in the calibration table. Several investigators [5–7] identified that noise present in the results obtained by color difference formula could be removed by taking into account the fringe order of the neighbouring resolved pixel. Quiroga et al. [5] proposed a window search method to refine the fringe order data and demonstrated it experimentally along a line in a loaded C-shaped specimen. Madhu and Ramesh [6] brought out that noise in TFP is due to the repetition of colours and proposed a noise immune colour difference formula which ensures a smooth variation of fringe orders. This approach was christened as Refined Three Fringe Photoelasticity (RTFP). Ajovalasit et al. [7] improved the work of Quiroga et al. [5] and arrived at a criterion for selecting the size of the window in the window search method. The scanning scheme adopted should be such that it is able to refine the entire domain of models having any complex shapes. In 2013, Kale and Ramesh [8] proposed a scanning scheme, called advancing front scanning in conjunction with multiple seed points to solve models of complex geometry.

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Ideally, calibration and application experiments should follow the same experimental conditions e.g. polariscope set up, ambient illumination and the camera settings in order to get accurate results. However in practice, there can be variations in the experimental conditions which can lead to false estimation of fringe orders. To eliminate this, the concept of colour adaptation was first introduced by Madhu and Ramesh [9] who proposed a single-point colour adaptation scheme using no-load bright field images of the calibration and application specimens. Later, Neethi Simon and Ramesh [10] proposed a two-point colour adaptation scheme, which only needs the isochromatic image of the model for adaptation.

The calibration table is generated using a beam under four point bending [1, 6], C-shaped specimen under tension [7] or an eccentrically loaded tensile specimen [11]. In 2015, Swain et al. [12] have proposed the use of theoretically generated calibration table which eliminates the need for separate calibration experiments provided the material stress fringe values (F_σ) are accurately known. The use of theoretically generated calibration table in conjunction with the normalisation of the isochromatic images will minimise the influence of experimental conditions as brought out in [13].

37.2 Normalisation of Isochromatic Image

Normalisation in image processing is a process that alters the range of pixel intensity values. Normalization transforms an image with intensity values in the range (*Min*, *Max*), into a new image with intensity values in the range (*newMin*, *newMax*). Several normalisation techniques have been proposed over the years. Fringe pattern normalisation generally involves two steps—background suppression and modulation normalisation [isotropic ndimension]. In 2001, Larkin et al. [14] proposed a method for fringe pattern normalisation using a two-dimensional quadrature which has connections with the Riesz transform in harmonic analysis. In the same year, Quiroga et al. [15] proposed an algorithm for fringe pattern normalization which uses two orthogonal band pass filters. The efficiency of the method is reduced in images with very low modulation regions or stepped contrast changes [16]. Later, Quiroga et al. [17] proposed another method of normalization using n-dimensional quadrature transform. However, the method needs pre-processing the fringe pattern to remove the bias term [16]. Guerrero et al. [18] proposed an iterative procedure based on the construction of an adaptive filter as a linear combination of isotropic bandpass filters. Ochoa and Silva-Moreno [19] introduced a method to formulate cosine profile of the fringe pattern which is based on the use of directional derivatives.

Swain et al. [13] have used the normalisation technique proposed in [14] for normalisation of the isochromatic fringe image TFP analysis. Following this work, in this paper, the normalisation scheme involving a high band pass filter for background suppression followed by the use of Hilbert transform is adopted. The calibration table is theoretically generated using the material stress fringe (F_σ) values corresponding to red, green and blue channels respectively. Though the method of normalisation has been successfully applied, an assessment of the performance of the method in relation to the fringe gradients in the model is lacking in the literature. This paper investigates the suitability of the method to solve problems having different fringe gradients.

37.3 Isochromatic Demodulation by Image Normalisation

Consider a problem of a circular disc made up of epoxy subjected to diametral compression (Load = 492 N, Diameter = 60 mm). The isochromatic data is obtained by TFP using a theoretically generated table in conjunction with image normalisation. The material stress fringe value of the model is measured as 13.52, 12.10 and 9.66 N/mm/fringe for red ($\lambda = 619$ nm), green ($\lambda = 546$ nm) and blue ($\lambda = 430$ nm) channels respectively. The theoretical generation of the calibration table is performed as detailed in [12]. The isochromatic image is first filtered to remove the low frequency background noise. A radius value (R) of 3 pixels is used for the high band pass filter. For comparison of the fringe order results, analytical obtained values are considered.

Figure 37.1 shows the plot showing the variation of the fringe orders along the horizontal diameter of the disc. It can be seen that the use of theoretical calibration approach yield results that closely follow the analytical values. The mean error in the fringe order was found to be less than 0.06. Hence, the simulated calibration table in conjunction with image normalisation is found to work well for this case. The subsequent sections discuss the performance of the method applied to problems involving high and low fringe gradient zones.

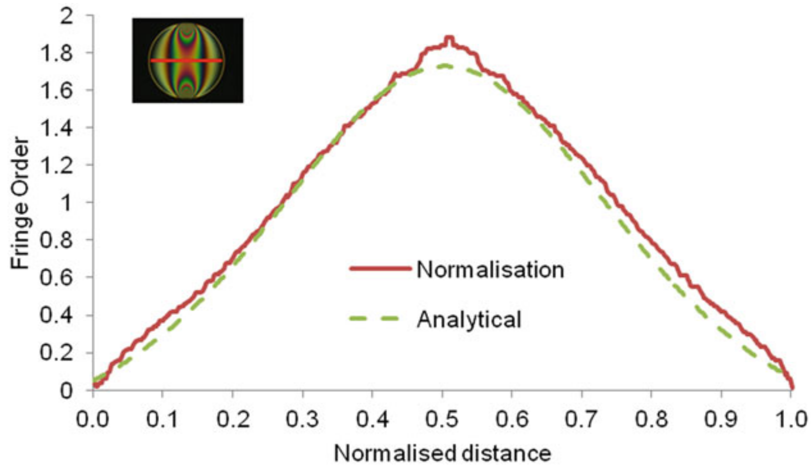

Fig. 37.1 Variation of fringe order values along the horizontal diameter of a disc under diametral compression (Load = 492 N) obtained experimentally using the theoretically generated table. Corresponding values obtained analytically are taken as the reference for comparison

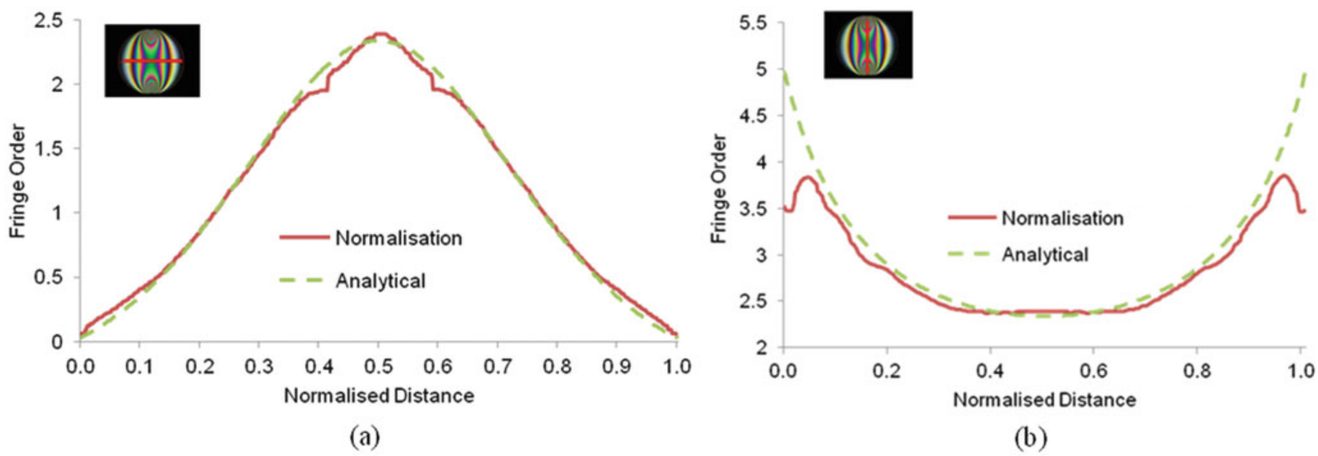

Fig. 37.2 Variation of fringe order values in a circular disc under diametral compression subjected to a higher load of 574 N obtained using normalisation along the (**a**) horizontal diameter, (**b**) vertical diameter. Values obtained analytically are taken as reference for comparison

37.3.1 High Fringe Gradient Zones

Next another circular disc specimen subjected to a higher load of 574 N is considered. The material stress fringe values of this disc are 12.01, 10.42 and 9.00 N/mm/fringe for red, green and blue channels respectively. The isochromatic image is normalised by the similar procedure adopted in the previous problem using $R = 3$. A line along the horizontal diameter gives consistent results with the analytical values (Fig. 37.2a) and the mean errors are found to be less than 0.04. When the fringe order values along the vertical diameter were analysed, it is found that isochromatics demodulation only till a fringe order of 3.7 is possible. However, the maximum perceivable fringe order in the model is close to 5 near the loading points of the disc. Hence, the method adopted is unable to correctly demodulate near the high fringe gradient zones.

It is found that the radius (R) of the high pass filter used for background suppression during normalisation affects the isochromatics demodulation in the high gradient zones. To study the influence of the radius of the high band pass filter, the isochromatic image of the disc is normalised using different values of R. Radius values of 2, 3, 7 and 12 pixels are considered for normalisation and Fig. 37.3 shows the variation of the fringe order values obtained after applying colour difference formula followed by refining each of them. It is seen that the isochromatic image normalised using higher radius filter gives better results in the high fringe gradient zones. Isochromatic demodulation of fringe orders upto 3.1 and 3.7 are obtained using radii 2 and 3 pixels respectively. The radii of 7 pixels and more are found to give a maximum fringe order of 4.7. Hence the use of higher radius value is recommended in problems involving a high fringe gradient.

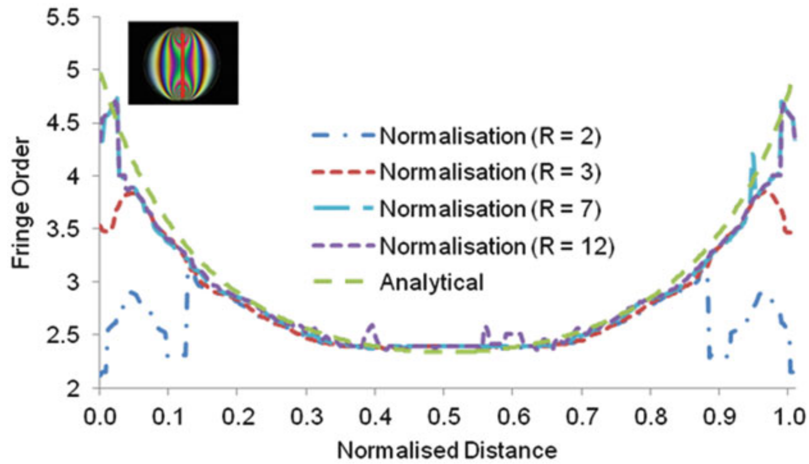

Fig. 37.3 Variation of fringe order values obtained in the circular disc subjected to a higher load of 574 N along the vertical diameter using difference radius values for background suppression. Values obtained analytically are taken as reference for comparison

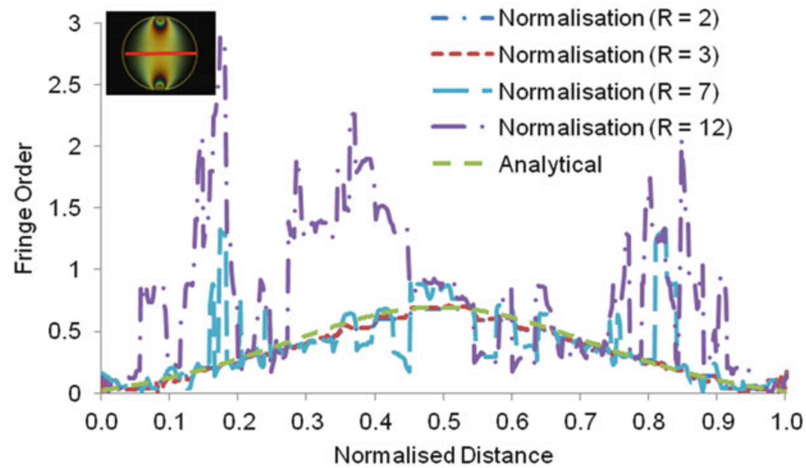

Fig. 37.4 Variation of fringe order values obtained in the circular disc under diametral compression subjected to a load of 174 N along the horizontal diameter using difference radii values for background suppression. Values obtained analytically are taken as reference for comparison

37.3.2 Low Fringe Gradient Zones

To assess the performance of the method in the low gradient zones, a circular disc subjected to a small load of 174 N is considered. The calibration table is theoretically generated using the material stress fringe values of 11.19, 10.01 and 7.9 N/mm/fringe for red, green and blue channels respectively. The dark field isochromatic image is normalised using different radii of the high band pass filter and demodulation is carried out using TFP.

Figure 37.4 shows the variation of the fringe orders along the horizontal diameter for radii values of 2, 3, 7 and 12. The fringe order values are compared with analytical results. It is found that the fringe order values obtained using a lower radius value ($R = 2$ and 3) gives good results and closely follow the analytical values. The use of higher R values makes normalisation sensitive to slight intensity variations in the model and amplifies them. It can be seen that the use of higher radii ($R = 7$ and $R = 12$) leads to false estimation of fringe orders. The absolute mean errors obtained are 0.031, 0.033, 0.129 and 0.500 fringe orders using radii of 2, 3, 7 and 12 pixels respectively. Hence, the use of low radii for the high pass filter are recommended for problems where the fringe gradient is small.

37.4 Conclusions

The performance of single colour image based twelve fringe photoelasticity using theoretically generated calibration table in conjunction with isochromatic image normalisation is studied for problems having a variety of fringe gradients. The use of normalisation has an advantage that it eliminates the need for experimental calibration provided the material stress fringe values of the photoelastic material is accurately known. However, in the present work, it is found that the radius of high pass filter used for background suppression during image normalisation affects the fringe order results. A lower value of radius is found to work well in the zones of low fringe gradient and a higher value of radius is required to demodulate isochromatics in the high fringe gradient zones.

For problems in which fringe gradients are uniform a single value of R for background suppression followed by normalisation is sufficient for isochromatics demodulation using TFP. However, in case of problems with varied fringe gradients, image normalisation using a single radius value throughout the model is insufficient to demodulate different zones of the model. Work on the development of appropriate normalisation scheme to solve such problems is currently underway.

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