AN ALTERNATIVE APPROACH TO UNWRAPPING PHOTOELASTIC PHASE DATA

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ABSTRACT
The use of digital photoelasticity in the form of phase-stepping is becoming more widespread which has lead to its use on industrial components particularly in the aerospace industry. In these applications the fringe patterns and component parts are usually complex and this can lead to difficulties when using conventional algorithms. The use of a combination of strategies to overcome these difficulties is described, leading to a more robust but equally fast algorithm for phase-stepping. The strategies that have been combined are: demodulation of the isoclinic fringe pattern using Wiener filtering and a 'zero-crossing' technique; a modified algorithm for calculating the retardation using a noise suppression approach and a logic operator to extend the periodicity; and a quality guided approach to unwrapping using the phase derivative variance to define quality. The new algorithm is demonstrated on a fringe pattern from a military aircraft under going full-scale fatigue testing.

INTRODUCTION
Photoelasticity allows the direct observation, via fringe patterns, of strains in transparent materials using polarised light. In reflection photoelasticity, a transparent polymer coating is bonded to an engineering component using a reflective adhesive. The coating acts as a strain witness and reproduces the strains experienced by the surface of the component. When the coating is illuminated with polarised light and viewed through a polarising element fringe patterns related to the direction and magnitude of the maximum shear stress are observed. Digital photoelasticity for the quantitative analysis of the fringes is becoming well-established [1] and its use is increasing. Three types of methods exist: spectral contents analysis, fourier methods and phase-shifting. For analysis of complete fringe patterns, spectral contents analysis is limited to RGB analysis and thus to isochromatic fringe orders of less than three. Fourier and phase-shifting methods require unwrapping of periodic distributions of the isochromatic fringe order but also provide isoclinic information unlike spectral methods. Many phase-shifting methods have been proposed but most differ only in the phase-steps employed and leave the fundamental drawback of the approach unsolved, namely that the result of phase-stepping is periodic maps of isoclinic and isochromatic fringes with undefined zones in the isoclinic maps at points with half-order fringe values (i.e. the relative retardation is zero) and with discontinuities in the periodic isochromatic map at points where the isoclinic is $n(\pi/4)$. This interaction of the isoclinic and isochromatic maps has been described in terms of signal modulation [2] and a process of demodulation and fuzzy set classification used to generate unwrapped maps of isoclinic and isochromatic fringe order. These processes have been demonstrated to be effective in many examples involving classical problems such as a disc in diametral compression and in a few industrial case studies mainly using three-dimensional photoelasticity to study aerospace components.

Table 1– Six-step schemes for digital transmission photoelasticity (Patterson & Wang, [2])

Image No	*f*	*b*	Light intensity
i_1	0	π/4	$i_1 = i_m + i_v \cos a$
i_2	0	-π/4	$i_2 = i_m - i_v \cos a$
i_3	0	0	$i_3 = i_m - i_v \sin a \sin 2q$
i_4	π/4	π/4	$i_4 = i_m + i_v \cos a \sin 2q$
i_5	π/2	π/2	$i_5 = i_m + i_v \sin a \sin 2q$
i_6	3π/4	3π/4	$i_6 = i_m - i_v \cos a \sin 2q$

However, the increasing popularity of digital photoelasticity and its use with reflection photoelasticity for industrial problems has generated a number of fringe patterns that have been found to be intractable using the methods described above for demodulation and for fringe unwrapping. The difficulties stem from a combination of sources including complex component geometry, wide ranges of fringe density and gradient within a small area and poor quality images. The latter can arise due to the diffuse nature of the reflection in most photoelastic coatings as well as from the ambient test conditions particularly when working under service conditions or in-situ on large-scale tests. These difficulties and the desire for a fast and robust algorithm lead to the exploration of an alternative approach to demodulating and unwrapping the phase maps obtained in digital photoelasticity. The new approach uses a Wiener filter and a 'zero-crossing' algorithm when demodulating the isoclinic data; a modified algorithm for the calculation of the isochromatic fringe order that includes noise suppression elements and a logic operator to extend the periodicity of the result; and a quality guided unwrapping algorithm for which quality is defined using the phase derivative variance. The method has some similarities to the regularised phase-tracking algorithm of Quiroga and Gonzalez-Cano [3] but differs in significant ways, not least in that it can be applied to a fringe pattern in seconds rather than minutes.

NEW METHODOLOGY

The new methodology is summarised in the flow chart shown in figure 1. The flow chart shows in the top left corner the isochromatic fringe pattern in a disc subject to compression across its vertical diameter viewed in a dark-field circular polariscope ((a) in figure 1). Along side this picture are the six intensity maps ((b) in figure 1) recorded using the orientations of the polariscope given in table 1. These are processed to generate a periodic map of isoclinic angle ((c) in figure 1) using the following equation:

$$q = \frac{1}{2}\arctan\frac{I_s}{I_c} \qquad (1)$$

where $I_s = i_5 - i_3$ and $I_c = i_4 - i_6$. This image is modulated by the isochromatic fringe order so that the isoclinic angle is undefined when the relative retardation is 0, π/2, π… In addition, the map is effectively composed of portions from two interlocking maps each of which is associated with a principal stress. This ambiguity needs to be removed in order generate a continuous map of isochromatic fringe order during subsequent stages of the process. The isoclinic angle is filtered by a Wiener filter which uses adaptive filtering to apply a low level of filtering when the variance is large and a high level when the variance is small. A zero-crossing technique is used to prepare the isoclinic for demodulation. This technique is similar to edge detection methods in image processing.

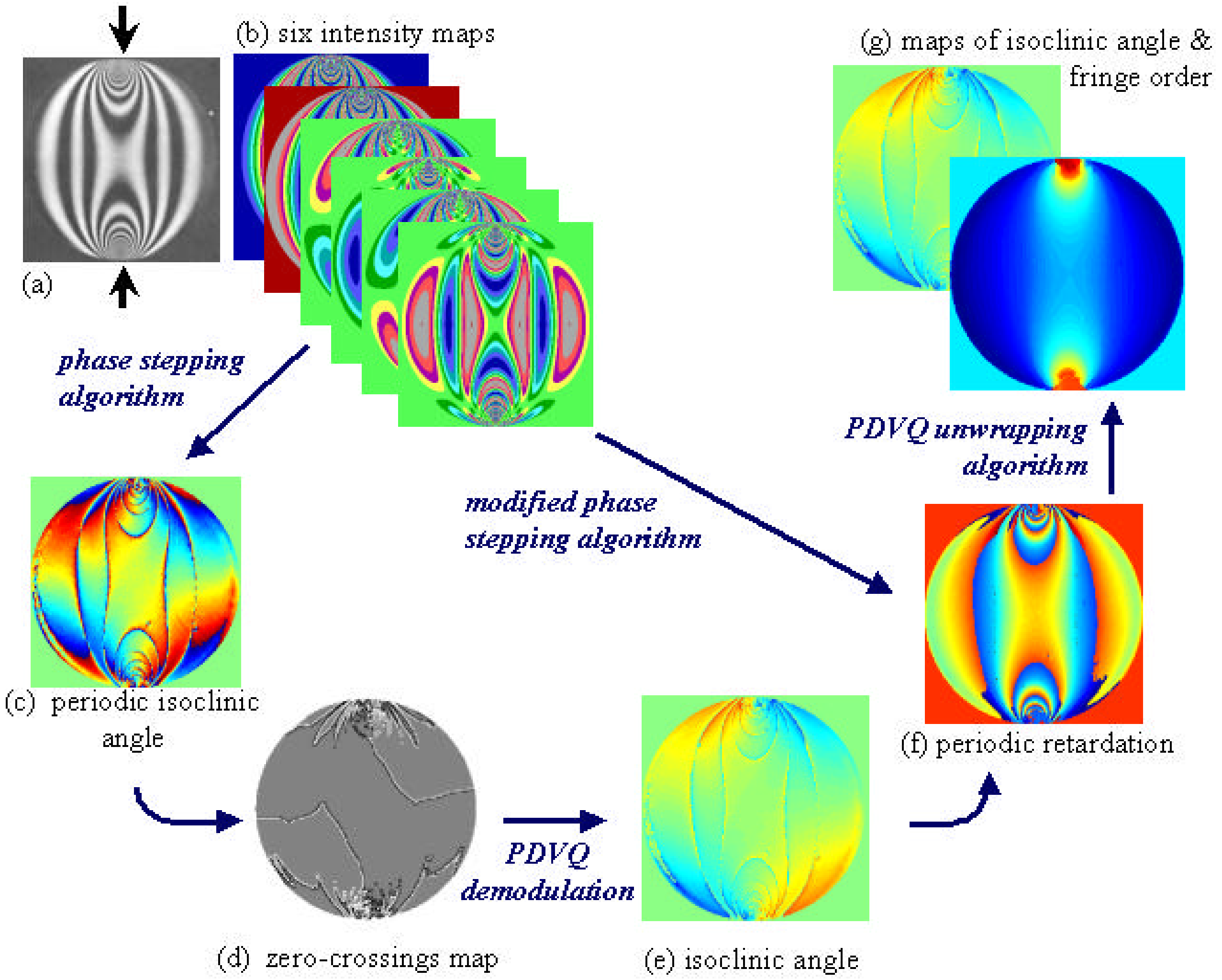

Figure 1 – Flowchart for the alternative approach to phase-stepping illustrated using simulated data for a disc in compression across its vertical diameter. The monochromatic dark field circular image, (a) is shown in the top left together with (b) the six phase stepped images collected using the polariscope orientations given in table 1. The initial calculation of the isoclinic (c to e) and retardation (f) data is performed separately and subsequently combined to generate the isochromatic fringe data, (g). The flow is essentially anti-clockwise to the result in the top right. (Note: PDVQ stands for phase derivative variance quality).

'Positive' and 'negative' matrices are created that are equal in size to the data array and initially populated with zero values. A raster scan of the isoclinic map is performed pixel by pixel with a two by two window formed by the pixels to the right, below and diagonally to the right of the pixel being considered. If the sign of all the isoclinic values in the window are the same then no action is taken and the scan moves on the next pixel, otherwise for those pixels in the window with negative values of isoclinic angle the corresponding zero in the 'negative' matrix is changed to one and similarly for the pixels with positive values. The scan continues so that when completed the location of all the zero-crossings is identified by unity values in the 'positive' and 'negative' matrices. Negative areas are defined as those enclosed by boundaries consisting of positive or upward steps or slopes in the isoclinic angle which occur at pixel locations defined by the unity values in 'positive' matrix, similarly positive areas are enclosed by a negative or downward steps or slopes in the isoclinic angle defined in the 'negative' matrix. The result is shown at the bottom centre left (d) in the flow chart in figure 1 with the positive areas outlined in white and the negative ones in black. These areas are subsequently unwrapped commencing from $A(i)$, which is best assumed to be the largest area, and employing a quality map, based on the phase derivative variance procedure proposed by Pritt [4] and described by Ghiglia and Pritt [5]. The boundary of $A(i)$ is searched for the highest quality pixel and the area on the other side of the boundary at this point is $A(i+1)$. When a discontinuity exists between areas $A(i)$ and $A(i+1)$ of magnitude between $\pi/4$ and $3\pi/4$ then value of the isoclinic angle for all points within $A(i+1)$ are translated by $-\pi/2$; similarly when a discontinuity between areas $A(i)$ and $A(i+1)$ of magnitude between $-\pi/4$ and $-3\pi/4$ is identified then all the points within $A(i+1)$ are translated by π/2. Then, the area *A(i+1)* is incorporated into *A(i)* and the pixel with the highest quality value on the new boundary is identified and the process repeated until all the areas have been considered. The result is shown at the bottom centre right (e) in figure 1. This map is used to correct the raw result obtained from equation (1), i.e. to create an isoclinic map which is demodulated but unfiltered and this result is employed with the six intensity maps to calculate a periodic map of relative retardation ((f) in figure 1) using the following equations:

$$a = 2p + \arctan\frac{I_s \cos 2q + I_c \cos 2q}{I_d} \quad \text{for } i_1 > i_2 \;\&\; i_4 < i_6 \qquad (2a)$$

$$a = p + \arctan\frac{I_s \cos 2q + I_c \cos 2q}{I_d} \quad \text{for } i_1 < i_2 \qquad (2b)$$

$$a = \arctan\frac{I_s \cos 2q + I_c \cos 2q}{I_d} \quad \text{otherwise} \qquad (2c)$$

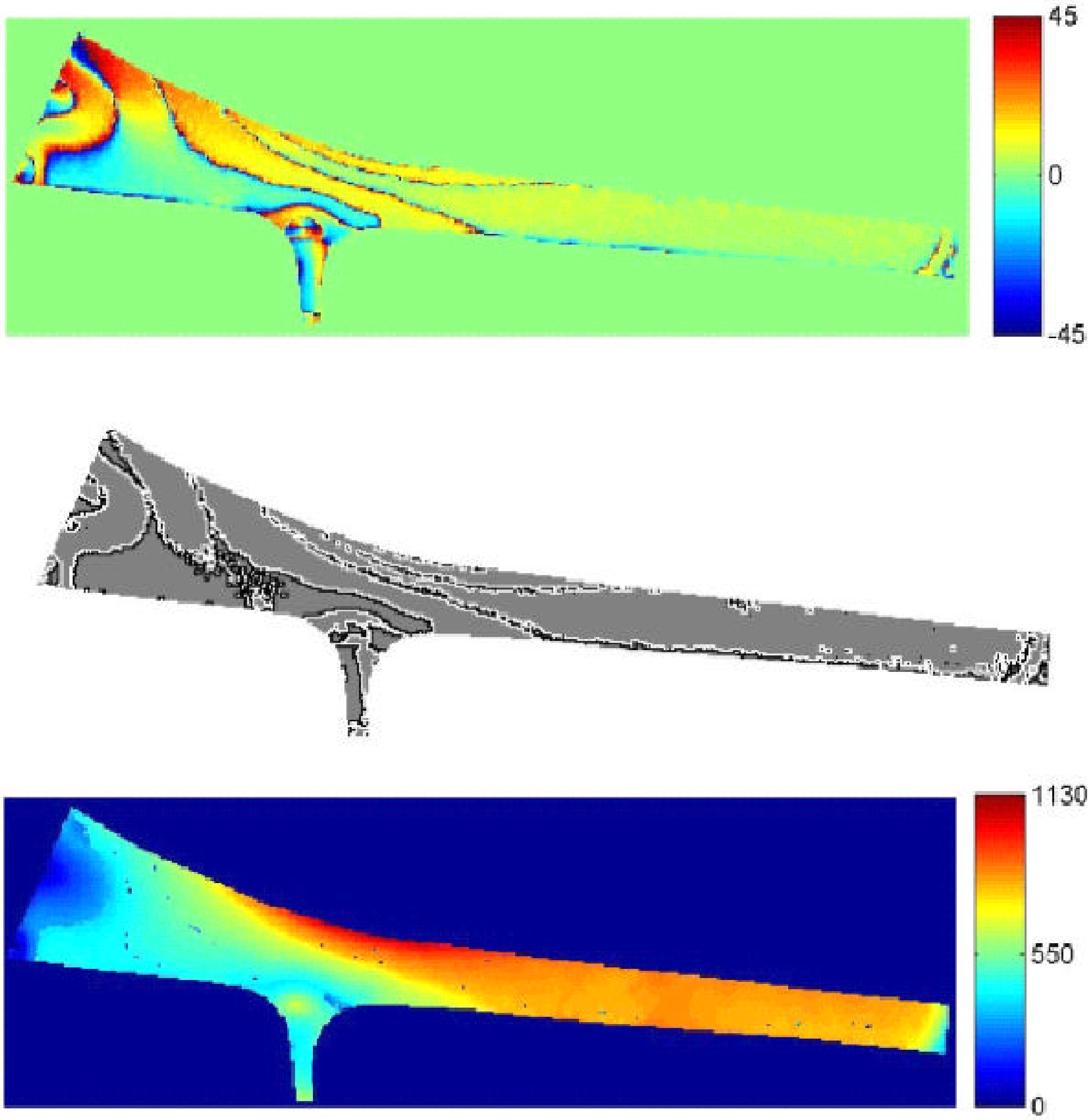

Figure 2 – Initial map of isoclinic angle (degrees) (*top*) obtained using expression (1) for a section of bulkhead in an aircraft, the corresponding areas in the map (*middle*) identified by the zero-crossing process; and the map of relative retardation (degrees) (*bottom*).

where $I_d = i_1 - i_2$. These equations combine the noise suppression approach suggested by Quiroga & Gonzalez-Cano [3] which involves using both I_s and I_c with the logic operator proposed by Sparling et al [5] which extends the period of the data from $\pi/2$ to π The result is shown in the bottom right of the flow chart. A quality guided unwrapping process is used to generate a continuous map of the relative retardation from the periodic map. The quality of each pixel is once again defined as the phase derivative variance but in this case the phase is taken to be the relative retardation. An algorithm developed by Heredia et al [6] for fringe projection was available and
was employed to unwrap the relative retardation. When a zero order fringe was present in the field of view no calibration of the isochromatic fringe order was necessary but otherwise it was necessary to provide the fringe order at a single point. Dependant on the location of the high quality points in the isoclinic and retardation maps it was sometimes necessary to invert the isochromatic fringe order distribution. This arises from the ambiguity of the isoclinic map which maybe associated with either principal stress direction. The resultant distribution is shown in the top left of figure 1.

RESULTS & DISCUSSION

An example of the process is shown in figure 1 for a two-dimensional disc pinched across the vertical diameter. The motivation for the work was to create a more robust algorithm for use on photoelastic fringe patterns generated in industrial applications. An example of this type of problem is shown in figure 2. A PS-1 coating (Measurements Group, Raleigh, NC USA) 1 mm thick was applied to the lower flange of the 488 bulkhead of a CF-18 military aircraft under-going a full-scale fatigue test. This location was identified as a critical area that would eventually require reinforcement using an aluminium reinforcing doubler. Due to the complex geometry of the bulkhead, photoelasticity was chosen to measure the full field, baseline strains in this region before the addition of the reinforcing doubler.

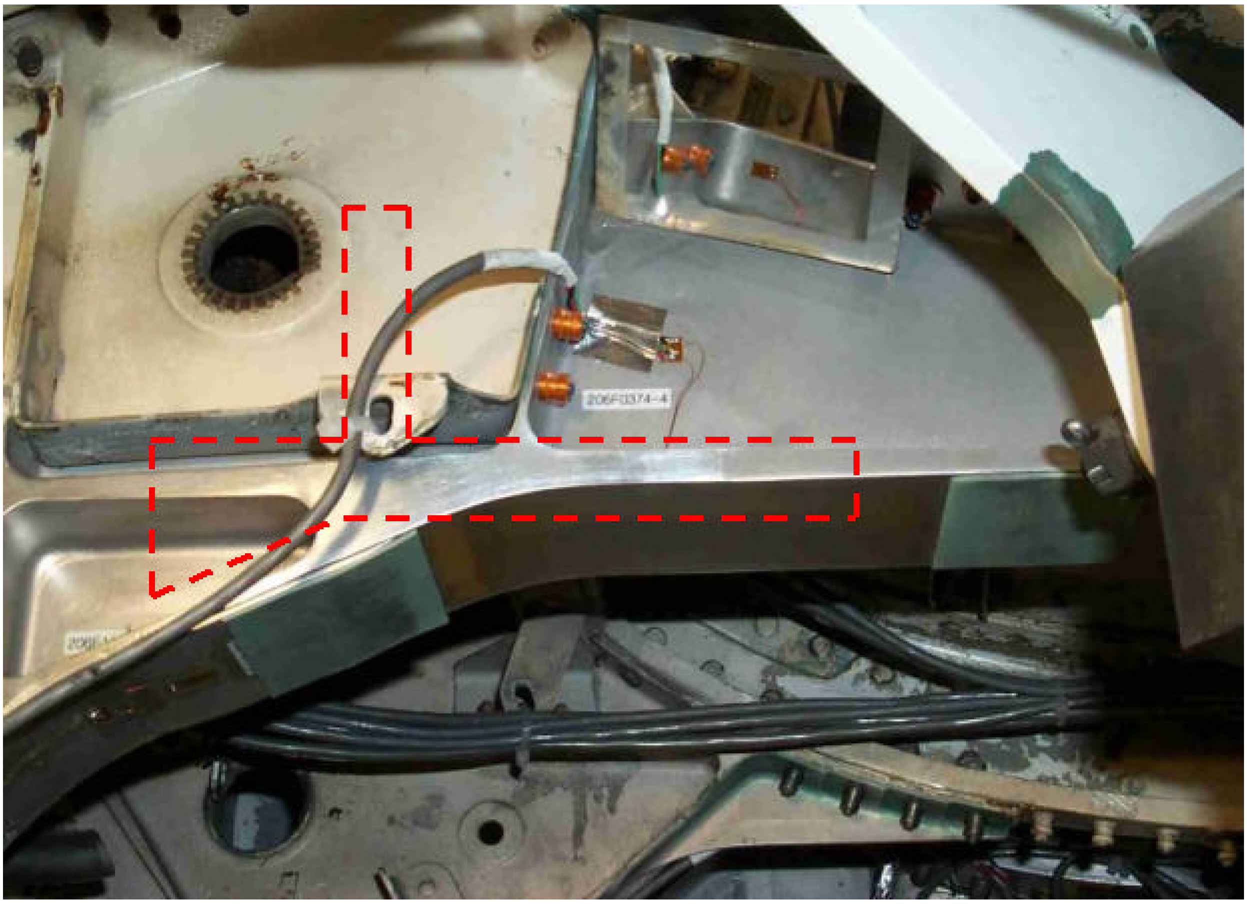

Figure 3: Y488 bulkhead with approximate location of photoelastic coating

The data was collected using a motor driven reflection polariscope that would automatically rotate the polarisers to the correct angle. Image collection was performed using a Sensicam QE (Cooke Corporation, Auburn Hills, MI, USA) CCD camera in ambient light conditions in an engineering test-hall. Six intensity images corresponding to those described in Table 1 were collected and processed in a few tens of seconds to generate the results presented. The initial isoclinic phase map is shown with the effect of the half order fringes clearly present. The zero-crossing boundaries are shown together with the unwrapped isochromatic fringe map. Processing the same data using the approach described by Wang and Patterson [2] resulted in several discontinuities in the isochromatic fringe order map.

CONCLUSION

An improved algorithm for the robust processing of phase-stepped photoelastic data generated from the use of reflection photoelasticity on industrial components particularly from the aerospace industry has been developed. A Weiner filter together with a quality guided process has been used to demodulate the isoclinic data which was generated from a six-step algorithm. Relative retardation was calculated from the six image data using a revised algorithm that combined elements for noise suppression with a logic operator that extend the period of the data. The relative retardation was unwrapped using an approach guided by a quality map for the pixels using the phase derivative variance to define quality for each pixel. The results suggest that the algorithm is comparable with respect to speed and superior in terms of quality compared to existing algorithms in use.

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