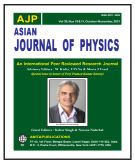

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P_Scope® – A virtual polariscope

K Ramesh

Department of Applied Mechanics, IIT Madras, Chennai- 600 036, India.

Dedicated to Prof Pramaod Kumar Rastogi for his outstanding contributions to Optical Metrology

P_Scope® is an innovative software that simulates the conventional polariscope using Jones calculus for ten different problems for which closed form solutions exist. It can help learn conventional photoelasticity as well as nuances of digital photoelasticity. The software is designed with a user-friendly interface that allows simulations using user defined problem parameters to suit their situations, thereby serving as a virtual laboratory.

Keywords: Photoelasticity, Polariscope, Stress, Polarization, Jones calculus, Isochromatic-, and isoclinic fringes.

1 Introduction

The optics required for photoelasticity is simple and hence it is easy to establish the experimental setup. Photoelasticity basically provides contours of constant principal stress/strain difference (*isochromatic* fringes) and constant principal stress/strain direction (*isoclinic* fringes). It could be used in transmission mode or in reflection mode [1-3]. Several problems could be studied just by observing the whole field nature of the fringe field. Fringe density is a useful parameter in identifying zones of stress concentration and zones where material could be removed for reducing the weight towards optimization! For quantitative data reduction, one needs to get the isochromatic and isoclinic value at any point. Ordering of the fringes is a skill to be learnt for any interferometric technique. One of the simplest ways to this is to observe the typical fringe patterns for a variety of problems. This is easily achieved by simulating fringe patterns using P_Scope® [4]. Due to the use of simulation, it is ideally suited for performing virtual experiments during restricted lab access during this pandemic.

As the software simulates solutions based on Theory of Elasticity, it also provides the theoretical values of fringe order and isoclinic value as recorded in a conventional polariscope. This feature helps in learning fringe ordering and to effect compensation techniques quickly at any point of interest. The software has two modes of compensation: Babinet-Soleil, and Tardy. The fringe fields are realistically simulated using Jones calculus and the student can understand the importance of determining the isoclinic angle at the point of interest first and the heuristic information that is extracted from the fringe fields for data interpretation. This knowledge can help one to appreciate the intricacies in the development of *Digital Photoelasticity*.

Use of *carrier fringe method* has been used in various experimental methods to augment the fringe field information. The software also has a feature to introduce carrier fringes of various densities at various angles to any of the selected models. A simple wedge type carrier is introduced by the simulation, whose parameters could be user defined. Use of carrier fringes has found applications in extracting data from poor birefringent materials like glass.

With advancements in digital imaging acquisition hardware, use of intensity information for data processing has come to stay and a new branch of *Digital Photoelasticity* has emerged and has stabilized in

Corresponding author
e mail: kramesh@iitm.ac.in (K Ramesh)

the last three decades [1,5]. The information of both isochromatic and isoclinic fringe order at every point in the domain can be easily determined by processing intensity data from multiple acquisitions. To achieve this, researchers have proposed unconventional optical setups. Since, Jones calculus is used, the software effectively simulates the intensity field for any specified set of orientations of the optical elements.

The software is also quite helpful in teaching various subtle concepts of solid mechanics such as concepts of stress concentration, shear stress variation, the principal stress directions being independent of the load in planar problems etc. For brevity, this paper confines to the basic simulation capabilities of the software.

2 Mathematics used to simulate the generic polariscope

The optical elements of a generic polariscope can be construed as a set of retarders to find the change in the polarization state of the incident light conveniently. If the orientation of the slow axis (θ) of the retarder and the retardation (δ) are known, then by Jones calculus [1-3], the retarder matrix is derived as:

$$\begin{bmatrix} \sin\delta/2 - i\sin\delta/2\cos 2\theta & -i\sin\delta/2\sin 2\theta \\ -i\sin\delta/2\sin 2\theta & \cos\delta/2 - i\sin\delta/2\cos 2\theta \end{bmatrix} \tag{7}$$

This provides the exit light vector with respect to the basic reference axes. Substitution of the relevant values in Eq (7) corresponding to the elements in a polariscope is sufficient to model its behavior. The polarizer may be aligned at an angle α and analyzer at an angle β. Thus, the light vector coming out of a generic polariscope setup can be easily obtained by a simple systematic matrix multiplication in complex domain using the Jones matrices in the sequence they appear along the light path. From the exit light vector, it is straightforward to determine the intensity of light transmitted.

This approach enables simulation of the conventional polariscopes by inserting various models for which closed-form solutions exist so that the retardation properties at the point of interest could be determined by calculating the principal stress direction as well as the principal stress difference at the point of interest.

3 Conventional photoelastic Arrangements

One of the benchmark problems used in photoelasticity is the problem of a disc under diametral compression. Figure 1(a) shows the fringe patterns simulated for an epoxy disc with a diametral load of 800 N.

The simulation has captured the fringe thickness variations normally seen in an actual experiment as well as the intensity of the background light. The basic parameters used for the simulation are mentioned in the header and footer of the image of the fringe patterns. The software has a feature to store these images at the click of a button to create a report of the simulations for easy documentation. In view of the theoretical simulation, the software also has a feature to mark the fringe orders and the principal stress directions at any point of interest, which are also shown in Fig 1(a).

One of the difficult ideas to communicate to students is change in the polarization state of the light after each optical element. The software P_Scope® has an elegant feature to show the wave propagation at any point in the image domain. The respective co-ordinates in mm as well as pixel dimensions are also forming part of the summary for easy documentation. This appears in the right side of the screen, and it has two parts: the top part shows the wave propagation, and the bottom portion shows the state of polarization.

By virtue of teaching the course several times to the students, the author has noticed that the two features, namely, marking the fringe orders and the principal stress directions along with the plot of wave propagation has phenomenally improved the easy grasp of the concepts of photoelasticity.

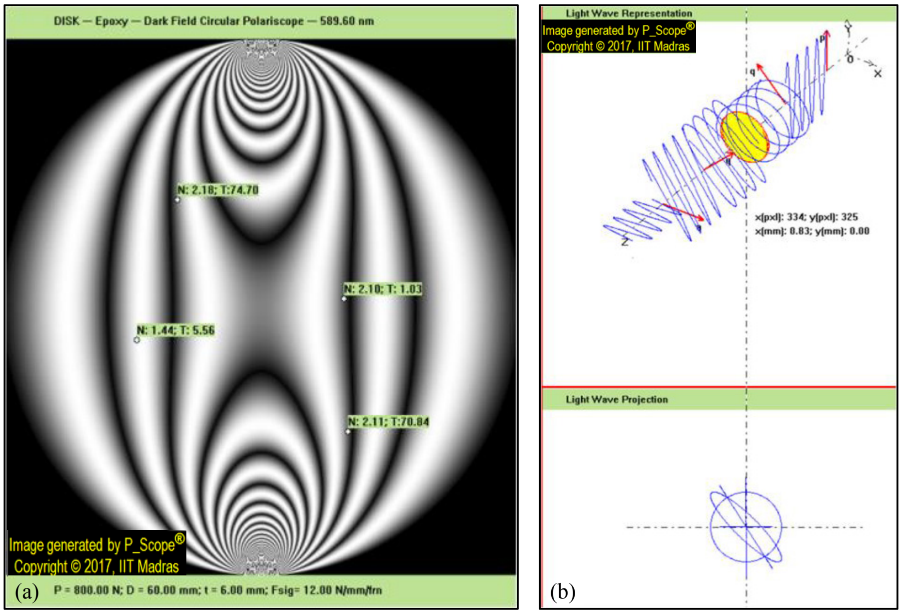

Fig 1. (a) Dark field isochromatics of a disc under diametral compression of diameter 60 mm and thickness 6 mm. (b) Plot of light wave propagation and light wave projection at the selected point.

4 Compensation Methods

P_Scope® software provides an interactive dialog to perform compensation to find the fractional fringe order at an arbitrary point using different methods. Two main methods of compensation are available in the software, namely, Babinet-Soleil compensation and Tardy's method of compensation. In both the methods, the first step is to find the isoclinic angle at the point of interest. The compensation dialog opens with 0^o isoclinic for any problem. The point of interest over the image is interactively selected using the cursor. In complicated fringe fields, it is desirable to also label the fringes in the vicinity of the point of interest (Fig 2).

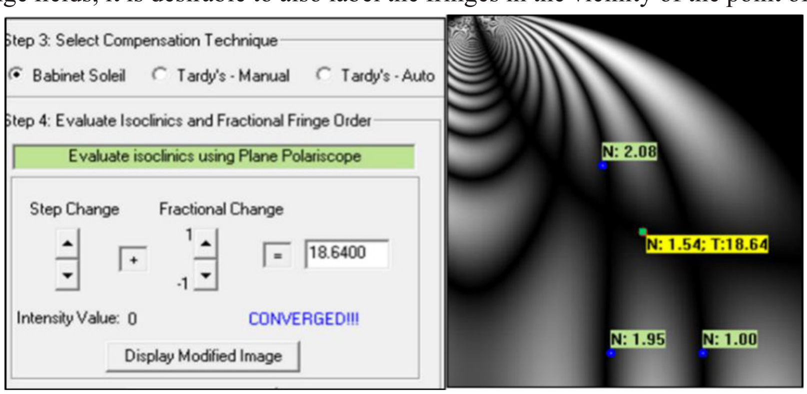

Fig 2. (a) Menu for selecting various compensation methods and to change the parameters by appropriate buttons. (b) The point selected and the isoclinics identified with the neighborhood points marked.

The selected point has the fringe order of 1.54 and the isoclinic angle is 18.64^o. The neighbourhood fringe orders are marked for concluding whether the higher order or the lower order fringe has moved to the point of interest upon compensation. To identify the isoclinic at the point of interest, the isoclinic value is entered by suitably varying the spin button values in the dialog box. The respective spin buttons can be used to change the integer and fractional part of the isoclinic angle. The software monitors the intensity of light transmitted and gives the intensity value as well as the comment whether the isoclinic value has converged or not [6].

In Babinet-Soleil compensation, the point of interest is viewed through a retardation plate of variable thickness used as a compensator and a knob is rotated thereby changing the thickness until a fringe passes through the point of interest. In the P_Scope simulation, changing the step value is equivalent to rotating the compensator. By changing this, one can dynamically see the movement of the fringe within the compensator (Fig 3).

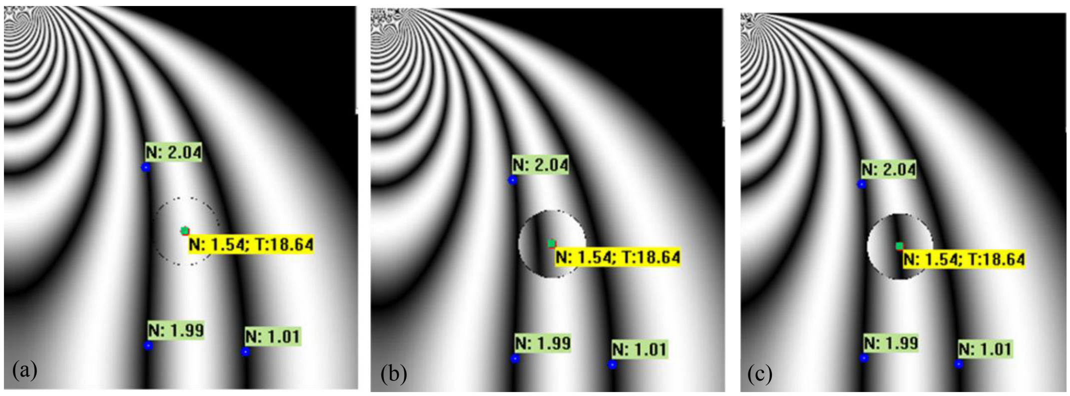

Fig 3. (a) Compensator aligned to the isoclinic angle is just placed at the point of interest. (b) – (c) The knob is rotated until the intensity at the point of interest becomes zero. By marking the neighborhood fringe orders, it is easier to see which fringe order has moved to the point of interest.

5 Carrier Fringes

Carrier fringes are used in several interferometric techniques to augment weak model information to make it measurable as the characteristics of the carrier fringes are completely known. The P_Scope® software introduces carrier fringes of a simple wedge starting from zero or a minimum fringe order. Use of carrier fringes is particularly useful in calibration of glass which is weakly birefringent. Figure 4 (a) shows a glass subjected to pure bending displaying very weak birefringence of just the zeroth order fringes occupying the entire beam. Figures 4 (b and c) show the resulting fringe pattern by superimposing a linearly varying carrier fringe field kept parallel to the beam and perpendicular to the beam axis, respectively.

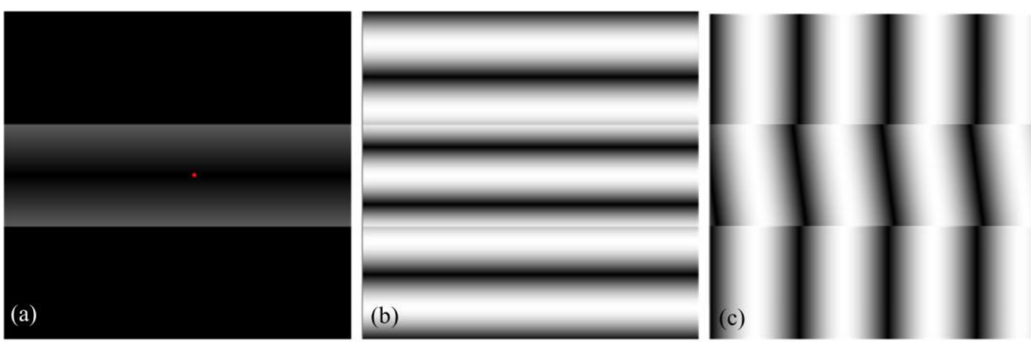

Fig 4. (a) Isochromatics in a glass beam subjected to pure bending. Composite fringe patterns are observed in the central beam region when a linearly varying fringe field is superposed: (b) Parallel to the beam (c) Perpendicular to the beam.

6 Additional Features

A special pop-up menu is designed that has two sub-menus; one to show fringe patterns/phase maps and the other to show stress component plots. Using the "fringe patterns" option, one can show for the problem selected, various fringe fields if white light is used. This can be advantageously used to learn fringe ordering using a color code which forms the basis for total fringe order photoelasticity (TFP) [5]. The dark field isochromatics for a disc under diametral compression is shown in Fig 5. Beyond twelve fringes, the simulation plots a color of red.

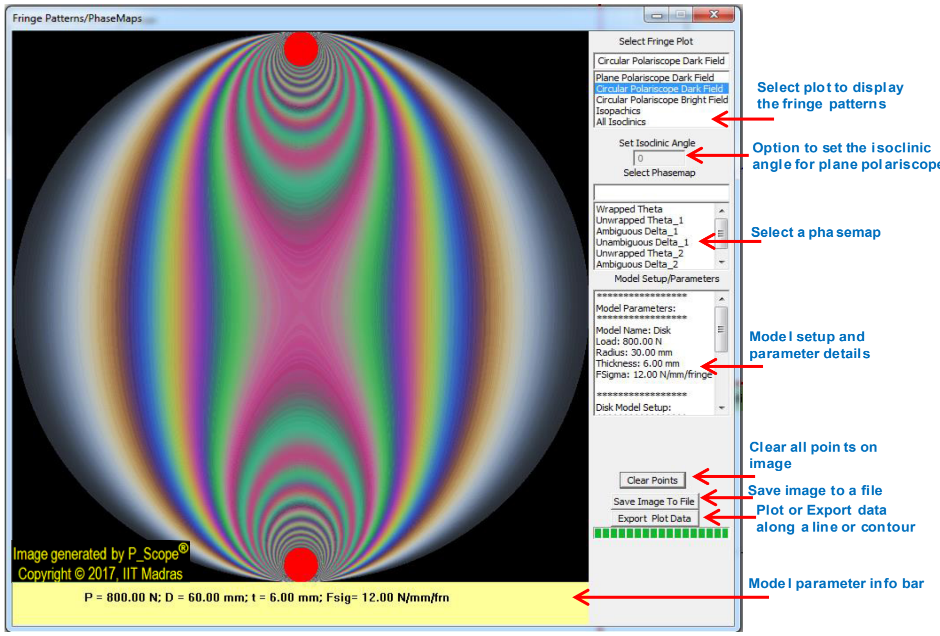

Fig 5. Dark field isochromatics simulated in the pop-up menu while using white light. The other menu options available are indicated - the red arrows indicate the menu option and its legend is given adjacent to that.

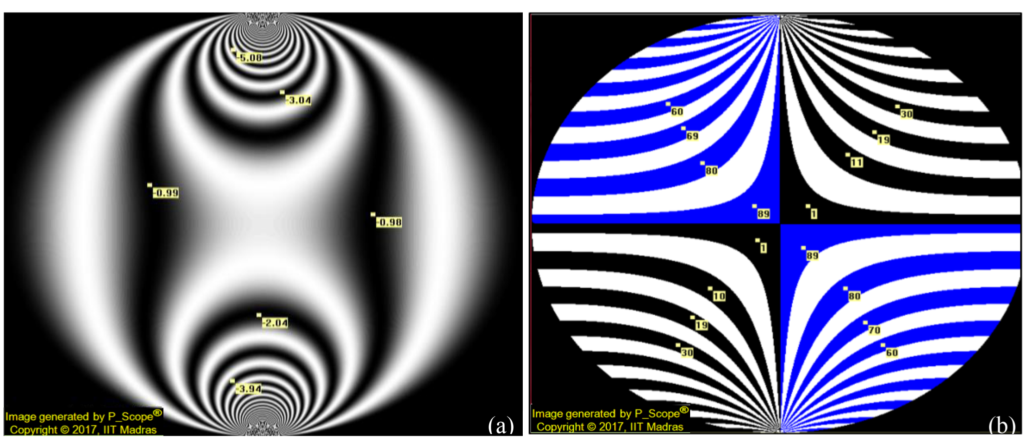

Fig 6. (a) Isopachic fringes (b) All isoclinics. The black contour corresponds to major principal stress and the blue contour corresponds to the minor principal stress.

Isopachics are contours representing the sum of principal stresses in a model obtained by Holography. Photoelasticity directly gives only principal stress difference. In conjugation with Isopachics (Fig 6(a)), it is possible to separate the principal stresses at any point of interest. In conventional photoelasticity, at any given time, one can observe only a particular isoclinic fringe. As this is a simulation module using theoretical solutions, it is possible to plot all isoclinics in one go unlike the conventional plane polariscope where for each isoclinic, the polariser and analyser combination has to be kept crossed for that angle and record only that isoclinic at a time. This enhances the understanding of the principal stress/strain directions and their variation over the field. In fact, in conventional photoelasticity, the isoclinic fringe features are used to order the isochromatic fringes [3]. The *all isoclinic* field (Fig 6 (b)) also shows whether a particular isoclinic displayed pertains to the major or the minor principal stress direction [4]. This is a valuable information, which has not been given much importance in general stress analysis.

Although the determination of isochromatic fringe order is quite simple in digital photoelasticity, the determination of isoclinics pertaining to major or minor principal stresses, though simple in conventional photoelasticity, has posed a challenge in digital photoelasticity. The use of inverse trigonometric functions in intensity processing has led to multi-valued solutions and though the range of principal stress directions is $-\pi/2$ to $\pi/2$, the mathematical equations give this only in the range $-\pi/4$ to $\pi/4$. So, the direct experimental calculations give both the major and minor principal stress directions in the range $-\pi/4$ to $\pi/4$ and the wrapped phasemap can be plotted by P_Scope® (Fig 7(a)). If one unwraps the major principal stress direction over the field, the phasemap appears as shown in Fig 7(b). If minor principal stress direction is unwrapped, it appears as in Fig 7(c) showing a π-jump along the horizontal and the vertical diameters. These are very subtle concepts, and all these can be easily simulated by P_Scope®.

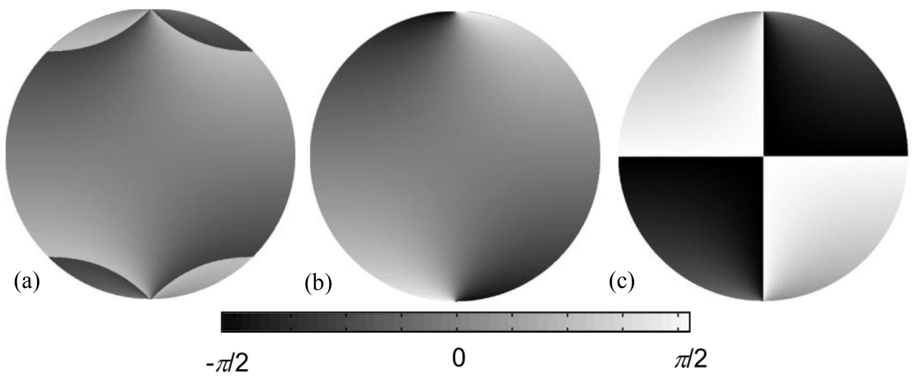

Fig 7. (a) Wrapped isoclinics. Unwrapped isoclinics representing: (b) Major principal stress direction. (c) Minor principal direction.

7 Closure

The various features of the software P_Scope® have been brought out succinctly in this paper. Several educational institutions across the world have started integrating it with their curriculum of experimental mechanics and solid mechanics which is expected to improve the standard of education in these areas.

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K Ramesh is currently the K Mahesh Chair Professor at the Department of Applied Mechanics, IIT Madras and formerly a Professor at the Department of Mechanical Engineering, IIT Kanpur. He has made significant contributions to the advancement of Digital Photoelasticity. This has resulted in a Monograph on Digital Photoelasticity - Advanced Techniques and Applications (2000), Springer, a chapter on Photoelasticity in the Springer Handbook of Experimental Solid Mechanics (2009) and a chapter on Digital Photoelasticity in the book on Digital Optical Measurement Techniques and Applications (2015), Artech House London. He has over 190 publications to date of which two have been reproduced in the Milestone Series of SPIE. His research has been funded by organizations such as ARDB, ISRO, DST, EU (FP7), and NSF. He received the Zandman award for the year 2012, the first Indian to receive it since its inception in 1989, instituted by the Society for Experimental Mechanics, USA for his outstanding research contributions in applications utilizing photoelastic coatings.

He has pioneered a new paradigm in Engineering Education by writing innovative e-Books on Engineering Fracture Mechanics and Experimental Stress Analysis published by IIT Madras. He has also given Video lectures of 40 hrs. each on Experimental Stress Analysis, Engineering Fracture Mechanics and Engineering Mechanics as part of the National Program for Technology Enhanced Learning (NPTEL), India. These lectures are available free on YouTube. Prof. Ramesh has also developed several educational software such as P_Scope®, DigiTFP®, DigiPhoto and PSIF for photoelastic analysis.

He is a Fellow of the Indian National Academy of Engineering since 2006. Received several awards such as Distinguished Alumnus Award of NIT, Trichy (2008), President of India Cash Prize (1984). Member of the Editorial Boards of the International Journals: Strain (since 2001), Journal of Strain Analysis for Engineering Design (2009-10), Optics and Lasers in Engineering, and Steering committee member of Asian Society for Experimental Mechanics since its inception in 2000.

For details see: https://home.iitm.ac.in/kramesh/index.html