Optics and Lasers in Engineering 105 (2018) 86–92

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Analysis of contact zones from whole field isochromatics using reflection photoelasticity

M.P. Haripras[a], K. Ramesh[b,*]

[a] Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham, Amritapuri, India
[b] Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai, India

ARTICLE INFO

Keywords:
Contact mechanics
Hertzian contact
Friction
Contact length
Reflection photoelasticity
Image processing

ABSTRACT

This paper discusses the method for evaluating the unknown contact parameters by post processing the whole field fringe order data obtained from reflection photoelasticity in a nonlinear least squares sense. Recent developments in Twelve Fringe Photoelasticity (TFP) for fringe order evaluation from single isochromatics is utilized for the whole field fringe order evaluation. One of the issues in using TFP for reflection photoelasticity is the smudging of isochromatic data at the contact zone. This leads to error in identifying the origin of contact, which is successfully addressed by implementing a semi-automatic contact point refinement algorithm. The methodologies are initially verified for benchmark problems and demonstrated for two application problems of turbine blade and sheet pile contacting interfaces.

1. Introduction

Contact zones which are present in the interface of multi-body systems are crucial as the stresses caused by the pressure distribution between the bodies in contact are of importance in the design of these parts. Photoelasticity is a non-contact whole field optical stress analysis technique, which can provide the information about the difference in principal stresses/strains and their orientation in the form of fringe contours. With advancements in digital photoelasticity [1–7], a number of techniques have been developed for the quantitative use of color information of the isochromatic fringe fields. Use of transmission photoelasticity in contact zone analysis has found its usefulness in a wide variety of problems ranging from mechanical contacts to biomechanics as well as granular materials [8–15]. However, availability of reflection photoelastic studies on contact problems is limited. In 2016, Frankovský et al. [16] used reflection photoelasticity to study the contact mechanics of a gear tooth profile. They extracted isochromatic data by means of tracing the integer fringe orders along a manually drawn fringe transition zones. Isochromatics obtained in reflection arrangement have low contrast and in contact regions it results in smudging of the fringes, which makes it difficult for data evaluation and also in judging the contact point origin.

This paper explores the use of reflection photoelasticity to study the contact zones using recent developments in digital photoelasticity. Isochromatic information in the vicinity of the contact zone is processed in color domain using TFP (Twelve Fringe Photoelasticity) [4]. Fringe order information in the vicinity of the contact zones are then used in a least squares sense to get quantitative information of the effective contact length and the friction between the contacts. A simple approach is implemented to improve the identification of the origin of the contact. The method developed is verified for benchmark problems and is then extended to evaluating contact stress parameters for two practical problems of turbine blade-hub and sheet pile interface.

2. Evaluation of contact stress parameters from reflection photoelasticity–analytical implementation

2.1. Isochromatic contours in reflection photoelasticity

Isochromatics obtained from reflection photoelasticity essentially provides the information of the principal strain difference (ε_1–ε_2), which in terms of principal stress difference can be written as

$$\varepsilon_1^c - \varepsilon_2^c = \frac{1+\nu_c}{E_c}\left(\sigma_1^c - \sigma_2^c\right) \tag{1}$$

where principal stress difference $(\sigma_1^c - \sigma_2^c)$ can be obtained from

$$\sigma_1^c - \sigma_2^c = \left(\sigma_{xx} - \sigma_{zz}\right)^2 + \left(2\tau_{xz}\right)^2 \tag{2}$$

In the case of non-conformal contact zones (Fig. 1), the whole field stress components are defined as [1,17]

$$\begin{Bmatrix}\sigma_x\\ \sigma_z\\ \tau_{xz}\end{Bmatrix} = \begin{bmatrix} -\frac{a}{\pi\zeta}\left[\left(a^2+2x^2+2z^2\right)\frac{z\psi_1}{a} - \frac{2\pi z}{a} - 3xz\psi_2 \right. \\ \left. +\mu\left\{\left(2x^2-2a^2-3z^2\right)\psi_2 + \frac{2\pi x}{a} + 2\left(a^2-x^2-z^2\right)\frac{x\psi_1}{a}\right\}\right] \\ -\frac{a}{\pi\zeta}\left(z\left(a\psi_1 - x\psi_2\right) + \mu z^2\psi_2\right) \\ -\frac{a}{\pi\zeta}\left[z^2\psi_2 + \mu\left\{\left(a^2+2x^2+2z^2\right)\frac{z\psi_1}{a} - \frac{2\pi z}{a} - 3xz\psi_2\right\}\right] \end{bmatrix} \tag{3}$$

* Corresponding author.
E-mail address: kramesh@iitm.ac.in (K. Ramesh).

https://doi.org/10.1016/j.optlaseng.2018.01.005
Received 24 September 2017; Received in revised form 22 November 2017; Accepted 8 January 2018

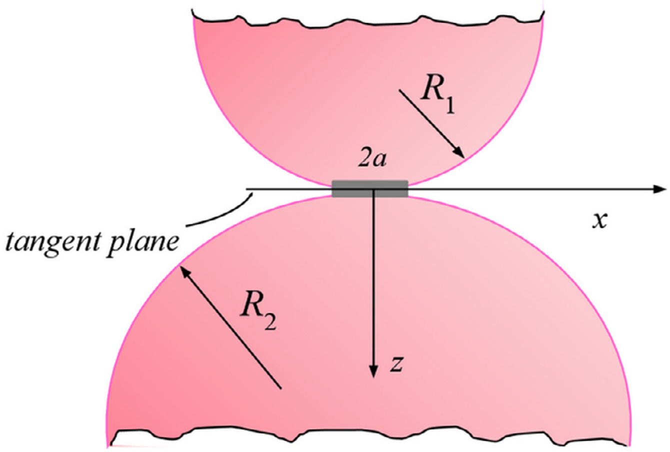

Fig. 1. Schematic diagram of two cylindrical bodies in contact.

where, $2a$ represents the semi-contact length (Fig. 1) and μ denotes the coefficient of friction at the contact. ζ is a function of the geometric and elastic properties of the bodies in contact and is given as,

$$\zeta = \frac{1}{\frac{1}{2}\left(\frac{1}{R_1}+\frac{1}{R_2}\right)}\left(\frac{1-{v_1}^2}{E_1}+\frac{1-{v_2}^2}{E_2}\right) \tag{4}$$

The parameters ψ_1 and ψ_2 are defined as

$$\psi_1 = \frac{\pi(r_1+r_2)}{r_1 r_2\sqrt{2r_1 r_2+2x^2+2z^2-2a^2}},\ \psi_2 = \frac{\pi(r_1-r_2)}{r_1 r_2\sqrt{2r_1 r_2+2x^2+2z^2-2a^2}} \tag{5}$$

where, $r_1 = \sqrt{(a+x)^2+z^2}, r_2 = \sqrt{(a-x)^2+z^2}$

Principal strain difference is related to retardation/fringe order by strain-optic law as

$$\varepsilon_1^c - \varepsilon_2^c = \frac{NF_\varepsilon}{2t_c} \tag{6}$$

where F_ε is the strain optic coefficient and t_c is the thickness of the coating. The retardation experienced by the birefringent material is a function of the wavelength (λ) of the light source used and strain-optic coefficient is usually expressed as $F_\varepsilon = \lambda/K$ where K is the strain coefficient which is usually supplied by the manufacturer or it can be measured by a calibration experiment too.

2.2. Evaluation of contact stress parameters from isochromatic data by least squares

From Eqs. (1) to (3), it is clear that (ε_1–ε_2) is non-linear in terms of a and μ. Combining Eqs. (1) and (3) and the strain-optic law (Eq. (6)), an error function is defined for the m^{th} data point in the model domain as

$$g_m = \varepsilon_1^c(a,\mu) - \varepsilon_2^c(a,\mu) - \frac{NF_\varepsilon}{2t_c} \tag{7}$$

Based on Taylor's series expansion, an error function can be expressed for i^{th} iteration as

$$-(g_m)_i = \left(\frac{\partial g_m}{\partial a}\right)_i(\Delta a)_i + \left(\frac{\partial g_m}{\partial \mu}\right)_i(\Delta\mu)_i \tag{8}$$

Application of Eq. (8) to m data points can be represented in matrix form as

$$\begin{Bmatrix} g_1 \\ g_2 \\ \vdots \\ g_m \end{Bmatrix}_i = -\begin{bmatrix} \frac{\partial g_1}{\partial a} & \frac{\partial g_1}{\partial \mu} \\ \frac{\partial g_2}{\partial a} & \frac{\partial g_2}{\partial \mu} \\ \vdots & \vdots \\ \frac{\partial g_m}{\partial a} & \frac{\partial g_n}{\partial \mu} \end{bmatrix}_i \begin{Bmatrix} \Delta a \\ \Delta\mu \end{Bmatrix} \tag{9}$$

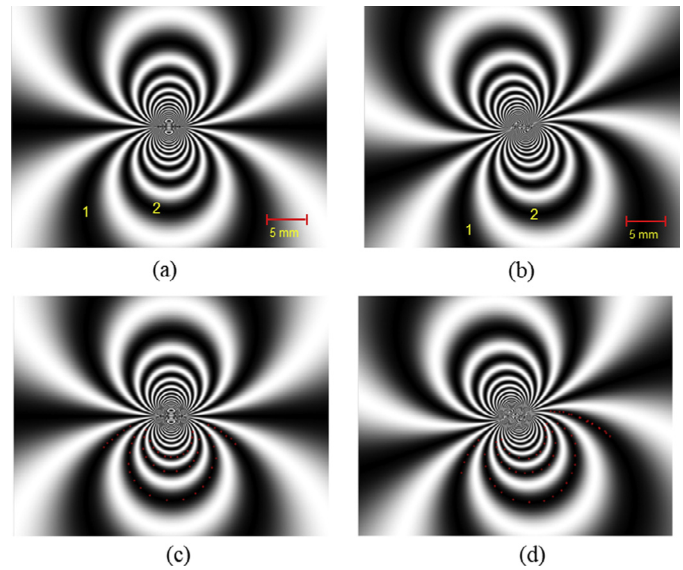

Fig. 2. Theoretically generated isochromatics in reflection photoelasticity for the contact zone with contact parameters of (a) semi-contact length $a = 1$ mm, frictional coefficient $(\mu) = 0$. (b) Semi-contact length $a = 1$ mm, frictional coefficient $(\mu) = 0.35$. Reconstructed isochromatics using the results of least squares analysis with the data points echoed back for the contact zone shown in c) Figure 2(a). d) Figure 2(b).

This set of equations are solved in an over deterministic approach and the parameters are then modified in the $i+1^{\text{th}}$ iteration. For transmission photoelasticity, the least squares procedure has been implemented by Shukla and Nigam [8]. They have used parameter minimization criteria for convergence evaluation, which may lead to false convergence. Here the non-linear least squares method is extended to process isochromatic data using fringe order minimization criteria for reflection photoelasticity. In fringe order minimization, the fringe orders corresponding to the selected data points are calculated theoretically during every iteration and are compared with the experimental fringe orders. The iteration is stopped if the convergence criterion is satisfied as

$$\frac{\sum\left|N_{\text{theory}} - N_{\text{exp}}\right|}{\text{no.of datapoints}} \leq \text{convergence error} \tag{10}$$

In order to study the implementation of the algorithm, analysis is carried out for theoretically generated isochromatic data with contact parameters $a = 1$ mm, $\mu = 0$ and $a = 1$ mm, $\mu = 0.35$ (Fig. 2(a) and (b)). Fringe order data and the co-ordinates are processed in non-linear least squares sense and the contact parameters are evaluated. The results obtained ($a = 1$ mm, $\mu = 1\text{e-}4$, convergence error $= 0.0035$ and $a = 0.998$ mm, $\mu = 0.352$, convergence error $= 0.0022$) are in good agreement with the actual values used for generating the analytical data and the reconstructed isochromatics from these parameters along with the data points echoed back is shown in Fig. 2(c) and (d). This indicates the correctness of the implemented procedure.

2.3. Automatic scanning procedure for contact point origin identification

The basic data for contact zone evaluation are the fringe orders and the corresponding positional coordinates with respect to the origin of the contact point. In the case of theoretically simulated contact zones, one knows the origin of the contact point. However, in the case of experimentally obtained isochromatics, Contact Point Origin (CPO) that is interactively picked up by the user needs to be improved.

The accuracy of the contact zone evaluation depends on the selected contact point origin. Hence, a semi-automated method for CPO refinement is established by extending the idea used for crack tip refinement in experimental fracture mechanics [18]. In this, the initial contact point is interactively selected by the user from the geometrical information of