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A low-level stress measurement method by integrating white light photoelasticity and spectrometry

Po-Chi Sung [a], Wei-Chung Wang [a,*], Chi-Hung Hwang [b], Guan-Ting Lai [a]

[a] Department of Power Mechanical Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan, ROC
[b] Instrument Technology Research Center, National Applied Research Laboratories, Hsinchu 30076, Taiwan, ROC

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ABSTRACT

To face the increasing demand of residual stress measurement in many hi-tech industries, the integration of photoelasticity and advanced image acquisition equipment is a natural trend. With the integration of photoelasticity and spectrometry, the measurement capability of low-level stress and the stress in low birefringence materials can be enhanced. In fact, there is a significant correlation between the stress level and transmissivity spectrum. The key of the stress measurement method proposed in this paper is to find this scarcely explored correlation. By analyzing the periodic extinction phenomenon of isochromatic fringe pattern obtained from white light photoelasticity and the equation of transmissivity spectrum expressed in stress and wavelength, a three-dimensional (3D) systematic relationship of transmissivity with stress and wavelength can be established. By applying the 3D systematic transmissivity with stress and wavelength, the stress value can be determined directly from the transmissivity of the light transmitted through the polariscope. Moreover, when the proposed method is employed, the required parameters can be directly obtained from the database. There is no need to know the wavelength-dependent stress-optic coefficient beforehand. Glass, a very low birefringence material, was used to confirm the feasibility of the proposed method. Two regression approaches to search the transmissivity extremities were attempted to find the optimum systematic relationship.

1. Introduction

In many hi-tech products, the residual stress is often one of main causes of the product failure. Therefore, the demand of the low-level stress (e.g. residual stress in general) measurement has been increasing. Photoelasticity [1] is the experimental optical method which can directly measure the stress. However, traditional photoelasticity is essentially impossible to analyze the low-level stress or the stress in low birefringence materials. Even with the introduction of the digital photoelasticity [2], the sensitivity and resolution of the digital image analysis systems used in the past still cannot completely fulfill the request of low-level stress measurement. Spectrometer is advanced image acquisition equipment that not only has fine capability to analyze the spectrum in detail, but also has high digital resolution and high sensitivity to light intensity. In the white light photoelasticity [3–13], the light intensity variation produced by the stress in the material corresponds to the variation of the stress at different wavelengths. By analyzing the variation information, the stress value can be accurately determined. Therefore, with the integration of the white light photoelasticity and spectrometer, the measurement capability of low-level stress and the stress in low birefringence materials can be enhanced.

The relationship between the stress level and color level, however, has not been thoroughly investigated. To accomplish the automatic measurement, piecewise information between the stress levels and corresponding color levels [3–10,12,13] was used in almost all past white light photoelasticity applications. Consequently, only pairs of stress value and color level exist in the database can be used to determine the stress. In fact, specific correlation between the stress level and color level does exist. Nevertheless, this specific correlation had been scarcely explored and used in white light photoelsticity. This specific correlation can be obtained by utilizing the periodic extinction phenomenon of the isochromatic fringe order in white light photoelasticity. However, by applying only this correlation in the stress measurement, the low-level stress corresponding to fringe order lower than 0.5 may not be effectively and accurately determined [14]. Therefore, by further integration of this correlation and the transmissivity

Abbreviations: TEToP, transmissivity extremities theory of photoelasticity; 1st LEMTE, linear equation of the first maximum transmissivity extremity.

* Corresponding author.
E-mail address: wcwang@pme.nthu.edu.tw (W.-C. Wang).

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equation derived from the photoelastic theory, a novel transmissivity extremities theory of photoelasticity (TEToP) [15] was developed for the low-level stress measurement. In this paper, the full derivation, methods and procedures of the TEToP are illustrated. The key of TEToP is to establish the three-dimensional (3D) systematic relationship of the transmissivity with stress and wavelength. By applying the established 3D systematic transmissivity with stress and wavelength, the stress value can be determined directly from the transmissivity spectrum of the light transmitted through the polariscope. In contrast to the conventional white light photoelasticity, the stress values to be measured will not be limited to the finite number of pairs of stress value and color level data in the database when employing TEToP. Moreover, the measurement time will be reduced and the inspection speed will be increased. Furthermore, there is no need to know the wavelength-dependent stress-optic coefficient beforehand. The parameters required in the measurement of TEToP can be directly determined from the database. In other words, TEToP is an ideal technique for precision measurement. In this paper, glass, a very low birefringence material, was used to confirm the feasibility of TEToP.

2. The proposed low-level stress measurement methodology

2.1. Transmissivity spectrum equation of isochromatic fringe order

Fig. 1(a) shows the dark-field circular polariscope. When the light source is white light, the intensity of light of wavelength λ transmitted through the polariscope can be represented by the following equation [2]

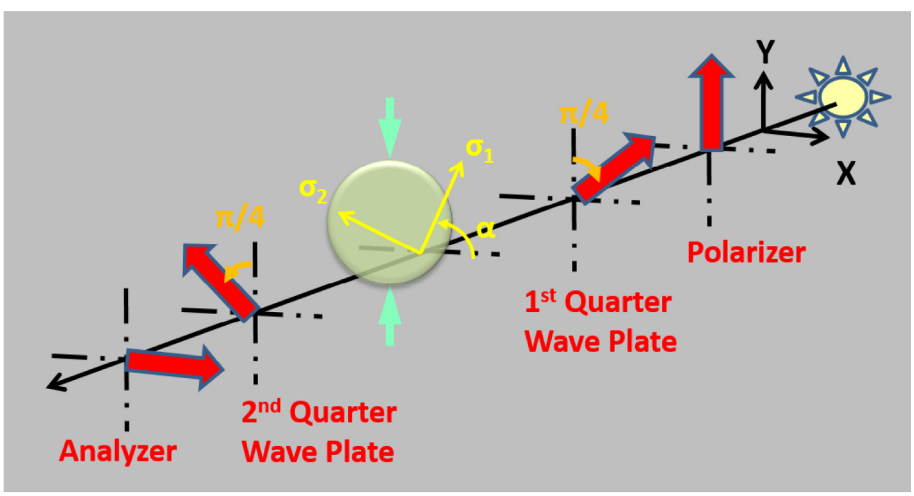
$$I(\lambda) = I_b(\lambda) + I_a(\lambda)[1 - \cos^2 2\alpha \sin^2 \varepsilon] \sin^2[\pi n(\lambda)] \tag{1}$$

where $I_b(\lambda)$ and $I_a(\lambda)$ represent the background and amplitude intensity of light of wavelength λ in the circular polariscope, respectively. $n(\lambda)$ is the isochromatic fringe order. Since quarter-wave plates are often of poor quality, the error introduced by imperfect quarter-wave plates (i.e. both quarter-wave plates differ from $\pi/2$ by a small amount) is indicated as ε [1]. To eliminate the principal stress angle α is set at $\pi/4$ or $-\pi/4$. Therefore, the light intensity equation of the isochromatic fringe order in circular polariscope can be obtained as

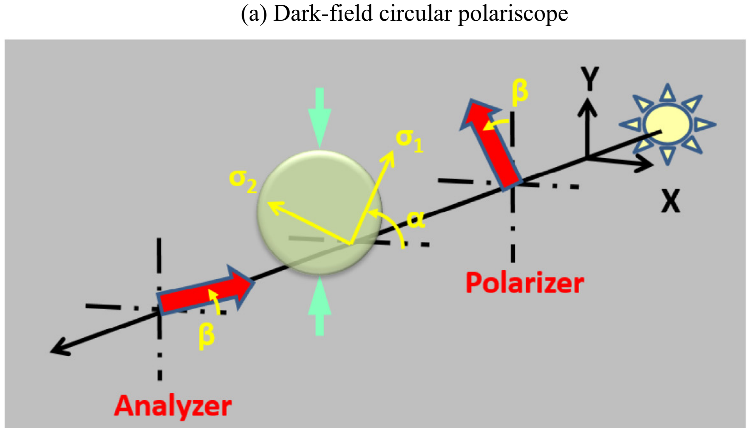
$$I(\lambda) = I_b(\lambda) + I_a(\lambda) \sin^2[\pi n(\lambda)] \tag{2a}$$

In practice, one can also obtain the light intensity equation of the isochromatic fringe order by applying two-step phase-shifting technique in a dark-field plane polariscope. Fig. 1(b) shows the dark-field plane polariscope. In Fig. 1(b), β is the polarization angle. The two light intensity equations in the two-step phase-shifting technique are shown in Table 1. In Table 1, $I_B(\lambda)$ and $I_A(\lambda)$ are the background and amplitude of light intensity in the plane polariscope, respectively. By adding both equations of Table 1 together, the light intensity equation of the isochromatic fringe order in plane polariscope can be acquired as

$$I(\lambda) = 2I_B(\lambda) + I_A(\lambda) \sin^2[\pi n(\lambda)] \tag{2b}$$



(a) Dark-field circular polariscope



(b) Dark-field plane polariscope

Fig. 1. Schematic diagrams of polariscopes.