Analysis of Optimal Polarization State Sampling Frequency Applied to Photoelastic Analyzer

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Abstract: In the paper, we proposed a low-cost photoelastic analysis system and used this system to measure the stress distribution of the doublet lens. The doublet lens was measured by four types of sampling frequency. The sampling frequency was 45 degrees, 22.5degrees, 11.25degrees and 5degrees. The different sampling frequency data was used to build a chart which was the relationship between measurement error and sampling frequency. The chart could help who used the method to choose a suitable sampling frequency and establish the most efficient process of stress measurement. In the future, we hope to improve the photoelastic analysis system to be fully automatic and apply it in the factory production line.

1 INTRODUCTION

In recent years, the optoelectronic industry has flourished, and optoelectronic products have been increasing day by day. The volume of optical products continues to shrink, but the resolution continues to improve. Therefore, the tolerance requirements of optical components have become more and more stringent. The problem of residual stress in optical components has gradually attracted attention. There will be residual stress during the production, assembly and operation of optical products The residual stress will directly affect the accuracy and life of the product. Therefore, analyze the internal stress of optical components and eliminate residual stress has become the most important problem in optical products.

Currently, the only way to measure the internal stress state of a component is photoelastic analysis(Holister, 1967). The measurement of photoelastic is used to measure the stress and strain on the surface or inside of the object by using the polarization state of the light wave after passing through the sample. In 1850 years, Maxwell proposed Stress-optic Law and established the theoretical basis of photoelastic analysis(Aben etc., 2012). Many researchers had published a lot of research on photoelastic analysis technology based on this theory. In 1979, Muller's team developed a fully automated photoelastic analyzer using cameras and image processing technology(Müller etc., 1979). The principle was to capture five images from 0 degrees to 90 degrees of isoclinic line and merged them into a contour map. The contour map was used to determine the internal stress distribution of the component. In 1986, Hecker's team developed a phase shift method for stress measurement (Hecker etc., 1986). The principle was to capture multiple images with different angles of polarization. These pictures were calculated by inverse trigonometric functions to obtain isoclinic angle and fringe order. The information of isoclinic angle and fringe order was used to determine the internal stress distribution of the component. In 1997, Petrucci's team combined the phase shift method with color imaging technology. It could reduce measurement errors caused by wavelength (Petrucci etc., 1997). In 1998, the Plouzennec team established a circularly polarized light source photoelastic analysis system. The system captured bright field and dark field images to analysis the phase distribution and derived

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the stress distribution from the phase distribution(Plouzennec etc., 1999).

In the traditional stress measurement technologies and equipment, it usually needed a long time and high-precision calibration or expensive components. Therefore, in the paper, we have established a photoelastic analysis system, a measurement process and a stress algorithm. The advantage of the system was low cost and short measurement time. In the last section of the paper, the photoelastic analysis system was used to measure the sample stress distribution with different sampling frequency. The different sampling frequency data was used to build a chart which was the relationship between measurement error and sampling frequency. The chart could help who used the method to choose a suitable sampling frequency and establish the most efficient process of stress measurement.

2 PHOELASTIC ANALYSIS SYSTEM INTEGRATION

The photoelastic analysis system was mainly composed of LED Light source, Linear polarizer, 1/4 waveplate, Band pass filter and imaging system. The relative position of the element of the system was shown in Fig 1. These elements were commercially available. These elements didn't require customized production, which could reduce the cost of system construction. The bill of material table was shown in Table 1.

Table 1: The Photoelasticity bill of material table.

Photoelasticity BOM		
Items		Discription
1.	Light source	Philips MR16 LED(4.2W) with diffuser and collimator
2.	Linear polarizer	Visible Linear Polarizing Film (Over 99% Polarizing Efficiency)
3.	1/4 waveplate	Polymer Achromatic Retarder (630-835nm)
4.	Band pass filter	Transmission wavelength : 440-450 nm pass
5.	Imaging System	STC-MCS163U3V ● H x V pixels : 1440 x 1080 ● Pixel pitch: 3.45 x 3.45 um ● Lens : M0814-MP2

In the system, there were several parameters that must be paid attention to stability of output energy, uniformity of spot irradiance, symmetrically of the spot and the element relative levelness, when assembling the system. In order to achieve high-precision stress measurement, we formulate an assembly and adjustment process, shown below:

- Element relative levelness: The illumination surface of light source was regarded as reference level. Each element level error should less than 1 um.
- Stability of output energy: The visible light sensor was used to measure the Light source intensity error at different times. The Light source intensity error should less than ± 1 uW within 30 minutes.
- Symmetrically of the spot and uniformity of spot irradiance: The symmetry and unformity of the spot was directly related to the inclination angle of the 1/4 waveplate. Therefore, fine-tune the 1/4 wave plate until the light spot was unformity and symmetrically distributed, shown as Fig 2.

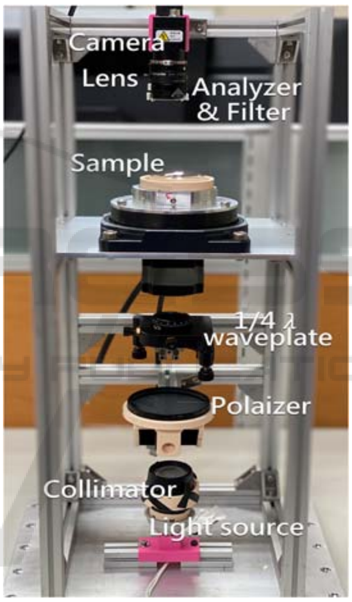

Figure 1: The photoelastic analysis system.

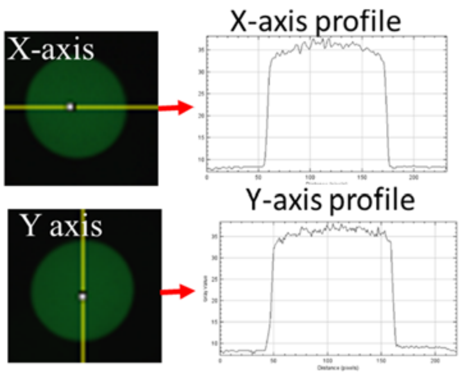

Figure 2: Analyze the symmetry and uniformity of the spot by the cross-section of the spot.

- Checking the light source polarization state: If the relative directionality of Linear polarizer and 1/4 waveplate was incorrect, the light will become elliptically polarized after passing through the 1/4 waveplate. Therefore, it was necessary to rotate the 1/4 waveplate so that its direction corresponds to the Linear polarizer. When the light source was circularly polarized, the intensity captured by the sensor was equal, even rotating the analyzer, shown as Fig 3.

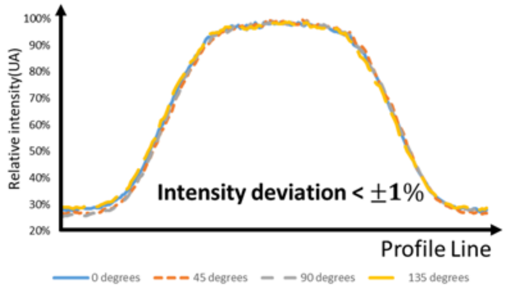

Figure 3: The light Spot intensity cross-section profile at the different angle of analyzer.

It was the photoelastic Analysis System assembly and adjustment process. After completing the above steps, you could start to measure the stress of the sample.

3 STRESS CALCULUS

The stress distribution and the phase difference distribution are in a proportional relationship. When the relative phase shift was measured, the relative stress distribution could be derived. Therefore, the stress measurement system should focus on how to obtain the phase shift quickly and accurately. For the phase shift and stress distribution formula was shown as Eq. (1)

$$\delta = \frac{2\pi t}{\lambda} C(\sigma_1 - \sigma_2) \qquad (1)$$

Where **δ** is Phase retardation, t is Object Thickness, C is Stress-optic coefficient and σ_1 & σ_2 is Principal stresses.

In the paper, we used the phase shift method to calculate stress. The principle was modulation the input light wave into a circular polarization state and analyze the polarization state of the light wave after passing through the sample. The measurement method of polarization state was to rotate analyzer and capture the intensity of light spot at different angle. According the different angle of sampling data, the polarization state of each pixel could be derived, shown as Fig 4.

When we got the polarization state of each pixel, the phase shift could be derived. The formula was shown below: Eq. (2)

$$cos\varphi = \frac{\tan(2\psi) * (E_{x'}^2 - E_{y'}^2)}{2E_{x'} * E_{y'}} \qquad (2)$$

Where φ is the phase, ψ is the elliptical orientation angle, E_x' is the maximum value of the E_x , E_y' is the maximum value of the E_y.

Put the phase shift of each pixel into the Eq. (1) and we could get the stress of each pixel. The process of stress calculus was shown as Fig 5.

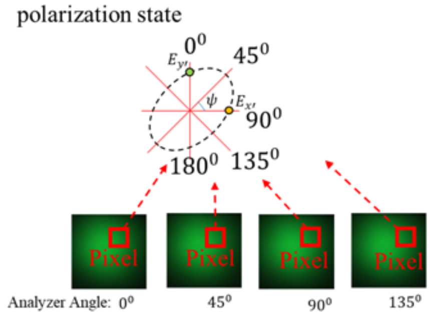

Figure 4: The method of polarization state calculus.

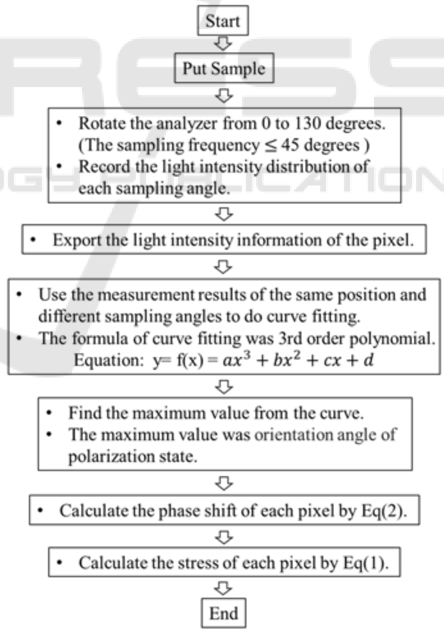

Figure 5: The process of stress calculation of photoelastic analysis system.

4 STRESS MEASUREMENT AND ANALYSIS

The previous section introduced the structure of the photoelastic analysis system and stress calculation method. The section presented the stress measurement results and a average stress measurement error chart. Here the doublet lens was used as a sample. The sample diameter is 50 mm and material is BK7. The material of glass lens does not have a lot of stress. The stress in the doublet lens mainly comes from the UV glue. In the experiment, the" Norland Optical Adhesive 61" was used to adhesive the double lens. The UV glue is cured by ultraviolet light with maximum absorption within the range of 320-380nm. The transmittance of UV glue is over 90 % in the visible light. The UV glue refractive index was 1.527 at liquid state. When the UV glue was cured, the refractive index increased to 1.563. Therefore, whether the glue was uniformly cured has a great influence on the internal refractive index. According to the optical theory proposed by Maxwell in 1853, the change optical refractive index of a transparent body was linearly proportional to the stress. The relationship was as follows: Eq. (3)

$$n_0 - n_1 = C(\sigma_0 - \sigma_1) \tag{3}$$

Where n_0 & n_1 is the refractive index of each principal stress direction in the material, C is Stress-optic coefficient and σ_0 & σ_1 is Principal stresses.

According the above formula, the internal stress of the doublet lens will be affected by the uniformity of illumination and the Curing time. The light source used in this experiment was a self-made UV light source. The irradiation area was about 4 inches, Irradiance uniformity > 90% @ irradiation area and the average of Irradiance was 5 mW/cm^2. Before the doublet glue lens was cured, the double glue lens needed to go through the process of glue dispensing, kneading and homogenization. Generally, the thickness of the doublet lens adhesive was 50um. The curing time usually needed 5 minute by self-made UV light source. In this experiment, the standard samples were produced according to the above-mentioned conditions.

Currently, Commercial stress measurement equipment available usually only measured information from four angles, and fitted the polarization state of each pixel through the information of the four angles. Because there were only four angle information, it was easy to cause errors. The easiest way to overcome this problem was to increase the sampling frequency, but frequent sampling will cause the measurement time to be too long. Therefore, this paper would conduct intensive sampling analysis and provided an optimal sampling frequency analysis based on the measurement results.

In this experiment, the sampling range was from 0 to 135 degrees and used 45 degrees, 22.5 degrees, 11.25 degrees and 5 degrees as the sampling frequency. In the Fig 6, it shown the stress distribution results at different sampling frequency. For easy analysis, the X-axis cross-sectional profile was obtained from the results of different sampling frequencies for analysis, shown as Fig 7. Because the 5 degrees was highest sampling frequency, we defined the measurement result of the 5 degrees sampling frequency was the standard reference value. According to the measurement results, when the sampling frequency was higher, the measurement error was smaller and closer to the reference value. When the sampling angle was 11.25 degrees, the stress cross section profile was almost overlaps with the standard reference profile.

In order to obtain the parameters between sampling frequency and measurement error, we used the 5 degrees sampling angle as the standard reference data, and calculated the average stress measurement error with the results of other sampling angles, shown as Fig 8. According the results, when the sampling angle was less than 15 degrees, the average stress measurement error was less than 5%.

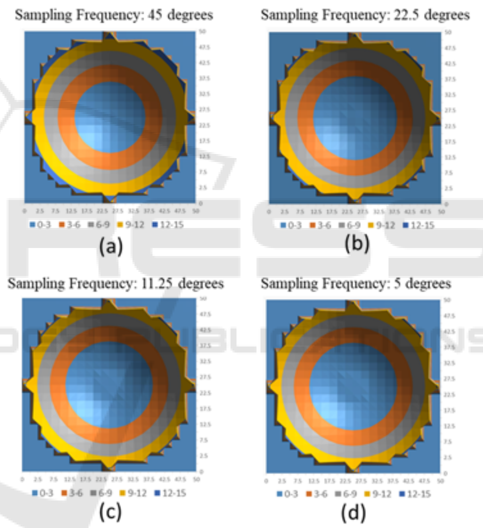

Figure 6: The results of stress distribution at different sampling frequency. (a) Sampling Frequency: 450. (b) Sampling Frequency: 22.50. (c) Sampling Frequency: 11.250. (d) Sampling Frequency: 50.

5 DISCUSSION

In the doublet lens, the UV glue will generate stress during the curing process. The stress will directly affect the effective focal length of the doublet lens. When the effective focal length changes, the optical quality of the imaging system will also decrease. Therefore, in the paper, we have established a photoelastic analysis system, a measurement process and a stress algorithm. The photoelastic analysis system was used to measure the sample stress distribution with different sampling frequency. The different sampling frequency data was used to build a chart which was the relationship between measurement error and sampling frequency. The chart could help who used the method to choose a suitable sampling frequency. In this experiment, the sampling range was from 0 to 135 degrees and used 45 degrees, 22.5 degrees, 11.25 degrees and 5 degrees as the sampling frequency. Among them, the 5 degrees data was used to be standard reference data and compared the reference data with the results of other sampling frequencies.

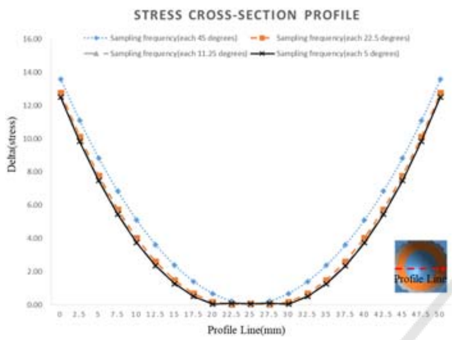

Figure 7: The chart of cross-section profile of stress.

According to the measurement results, when the sampling frequency was higher, the measurement error was smaller and closer to the reference stress distribution. When the sampling angle was 11.25 degrees, the stress cross section profile was almost overlaps with the standard reference profile. In order to obtain the parameters between sampling frequency and measurement error, we used the 5 degrees sampling angle as the standard reference data, and calculated the average stress measurement error with the results of other sampling angles. According the results, when the sampling angle was less than 15 degrees, the average stress measurement error was less than 5%. If people want to keep the measurement speed and accuracy, the recommended sampling frequency angle of photoelastic analysis system was 15 degrees.

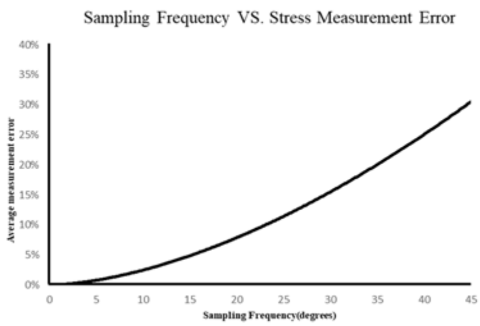

Figure 8: The chart of average stress measurement error.

6 CONCLUSION

In the paper, we proposed a low-cost photoelastic analysis system and used this system to measure the stress distribution of the doublet lens. The doublet lens was measured by four types of sampling frequency. The sampling frequency was 45 degrees, 22.5degrees, 11.25degrees and 5degrees. We used the measurement stress curve of 5 degrees to be a reference. When the sampling frequency was increased, the measure stress curve was closed to the reference curve. Finally, we used the error of different sampling frequency to build up a sampling frequency and measurement error curve. Users could set the sampling frequency according to their own measurement accuracy requirements. In the future, we hope to improve the photoelastic analysis system to be fully automatic and apply it in the factory production line.

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