Magneto-optical modulation measurement method of glass internal stress

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Abstract: In order to achieve the high-precision measurement of glass internal stress, a new method of magneto-optical modulation was proposed, and the system of internal stress measurement based on the magneto-optical modulation was established. First, measurement model of the system was derived according to the Mueller matrix description method of polarized light, by using separation of the direct current, fundamental frequency and the second harmonic component of detected signals, and "normalized" approach, the impact of the light source intensity fluctuation on the measurement result was eliminated. The direction of glass internal stress and the size of stress birefringence values were received by processing the respective signal components. By measuring the glass at different positions, the validity of the method is verified, and the measurement accuracy of internal stress direction is 5″, the measurement accuracy of stress birefringence value is below 0.5 nm/cm. This system has high stability and high accuracy.

Key words: optical glass; stress measurement; stress birefringence; magneto-optical modulation

CLC number: TQ171.11 **Document code:** A **Article ID:** 1007-2276(2015)03-0911-06

磁光调制法测量玻璃内应力

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摘 要: 为了实现玻璃内应力的高精度测量,提出了一种磁光调制的新方法,建立了基于磁光调制的内应力测量系统。首先,根据偏振光的穆勒矩阵描述方式推导了该系统的测量模型,通过分离被测信号的直流、基频和各次谐波分量,并利用“归一化”的方法,消除了光强波动对测量结果的影响,并根据处理接收到的各信号分量得到玻璃内应力方向和应力双折射大小。通过测量玻璃的不同位置验证了该方法的有效性,内应力方向的测量精度为 5″,应力双折射的测量精度低于 0.5 nm/cm,且系统具有稳定性高、精度高等特点。

关键词: 光学玻璃; 应力测量; 应力双折射; 磁光调制

收稿日期: 2014-07-10; **修订日期:** 2014-08-16

基金项目: 国防科研基金(JPPT-115-3-1360)

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0 Introduction

In the design of the optical system, well processed surface of the optical part will be deformed over time when the glass inner stress exists, which affects the image quality seriously. The quality of optical uniformity will also be reduced by uneven distribution of stress with the refractive index distribution is inconsistent; all of these will make the wave surface deformed through the optical glass, so that the image qualitative goes to the bad[1]. Therefore, measuring the size of the internal stress in optical glass and determining its distribution law in order to ensure the glass accuracy are the problems that glass material design and production department as well as the optical designers most concern about. Stress measurement is not a difficult work, but it involves many factors that are easy confused, it will get error or even the opposite results easily with drawing a little attention[2]. Before the actual measurement, we must analyze the stress factors cause the failure of glass products firstly, clarify ideas, and choose a reasonable method of measuring step. There are many ways to measure the glass stress birefringence, such as polarization interference method, the 1/4 wave plate method, the intensity ratio method, Tardy quantitative test method, Babinet compensator method, electro-optic modulation of KD*P crystal method and so on[3-5]. In addition to the electro-optical modulation method, other methods have the disadvantage of insensitive to the accurate measurement, these cannot achieve smaller stress birefringence measurement, and the device performance is not reliable when used in the harsh environments of the industrial field, these cannot meet the requirements of high accuracy measurement[6-7]. The measurement precision of electro-optical modulation method is affected by stability of modulation voltage, electro-optic crystal and 1/4 wave plate optical axis adjustment accuracy and the stability of light source wavelength; it has greater difficulties in project implementation, and is difficult to develop a practical and reliable system of inner stress measurement[8]. And in order to achieve high-precision measurement, we generally choose to increase the length of the sample, based on the assumption that the total internal stress is increased linearly with the length to obtain a stress value in the unit length[9-10]. In fact, in the inside of the low-stress material, the distribution of the internal stress is complex, and the directions are diverse, this measurement is difficult to represent the real situation of the actual parts, therefore we need to configure a high-precision inner stress detection equipment to ensure the quality of the sample. In this paper, a high-precision measurement method of glass internal stress based on magneto-optical modulation technology is raised, which has solved the technical difficulties of the above methods.

1 System compositions and working principle

The magneto-optical modulation method is based on the magneto-optical glass under the external magnetic field can become optically active device, and related to the applied magnetic field direction, it rotates the polarization direction of linearly polarized light propagating from this glass, that is to say it occurrences Faraday effect. We obtain the linearly polarized light from the laser light source with a collimating lens emits a light beam which transmits from the polarizer, the linearly polarized light becomes modulated polarized light, and its polarization direction has a deflecting swing angle of θ when it transmits from the modulated magneto-optical glass with a external sinusoidal alternating magnetic field, wherein the magnetic field direction and the optical axis are uniform; modulated signal light passes through the sample, and an analyzer, and reaches the photoelectric detector in turn. The structure of the measurement system is shown in Fig.1, P_1 P_2 is the polarizer and analyzer respectively, and we set the polarized direction of polarizer as x axis.

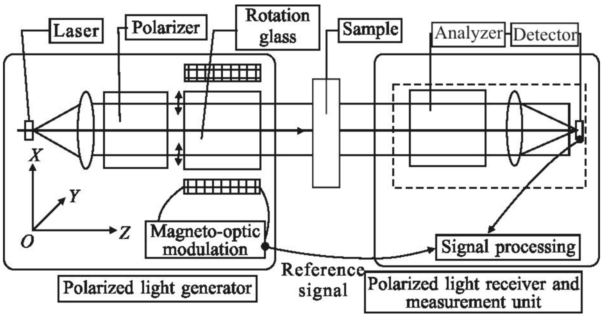

Fig.1 Structure of the measurement system

θ is the magneto-optical modulation angle, δ is the birefringent phase of the sample, γ is the sample fast axis relative to the angle of the polarizer axis, β is the analyzer axis relative to the x axis. When we make it a condition that the polarizer direction is x axis, the Mueller matrix of the magneto-optical modulator is R, which is expressed as below:

$$R=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos2\theta & -\sin2\theta & 0 \\ 0 & \sin2\theta & \cos2\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Wherein $\theta=\theta_0\sin\omega t$, θ_0 is the angular amplitude of the magneto-optical modulation, ω is the magneto-optical modulation frequency. The Stokes vector of linearity polarized light beam emitted from the polarizer is P_1, the Mueller matrixes of the test sample S and the analyzer P_2 are as follows:

$$P_1=I_0\begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

$$S=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1-(1-\cos\delta)\sin2\gamma & (1-\cos\delta)\sin2\gamma\cos2\gamma & -\sin\delta\sin2\gamma \\ 0 & (1-\cos\delta)\sin2\gamma\cos2\gamma & 1-(1-\cos\delta)\cos^2 2\gamma & \sin\delta\cos2\gamma \\ 0 & \sin\delta\sin2\gamma & -\sin\delta\cos2\gamma & \cos\delta \end{bmatrix} \tag{3}$$

$$P_2=\frac{1}{2}\begin{bmatrix} 1 & \cos2\beta & \sin2\beta & 0 \\ \cos2\beta & \cos^2 2\beta & \sin2\beta\cos2\beta & 0 \\ \sin2\beta & \sin2\beta\cos2\beta & \sin^2 2\beta & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

Wherein, I_0 is the intensity of light beam out of the polarizer. The matrix of the radiation light beam from the analyzer is

$$T=P_2SRP_1 \tag{5}$$

As the photoelectric detector can only detect the light intensity value, then the light intensity I that detector received is the first term value of the Stokes vector T:

$$I=\frac{1}{2}I_0G(1+A\cos2\theta+B\sin2\theta) \tag{6}$$

Wherein

$A=(\cos^2 2\gamma+\cos\delta\sin^2 2\gamma)\cos2\beta+(1-\cos\delta)\sin2\gamma\cos2\gamma\sin2\beta$,

$B=(\sin^2 2\gamma+\cos\delta\cos^2 2\gamma)\sin2\beta+(1-\cos\delta)\sin2\gamma\cos2\gamma\cos2\beta$

In the formula (6), G is the photoelectric gain coefficient, since $\theta=\theta_0\sin\omega t$, by expanding the formula (6) with the first class Bessel function and we find that:

$$I=\frac{1}{2}I_0G\{1+AJ_0(2\theta_0)+2BJ_1(2\theta_0)\sin\omega t+ 2AJ_2(2\theta_0)\cos2\omega t+\cdots\} \tag{7}$$

By amplifying and filtering the output signal, the DC component is:

$$I_{dc}=\frac{1}{2}k_0[1+AJ_0(2\theta_0)]I_0 \tag{8}$$

The fundamental frequency component is:

$$I_{1f}=\frac{1}{2}k_1\cdot 2BJ_1(2\theta_0)I_0 \tag{9}$$

The second harmonic component is:

$$I_{2f}=\frac{1}{2}k_2\cdot 2AJ_2(2\theta_0)I_0 \tag{10}$$

Wherein, k_0, k_1, k_2 are the photoelectric conversion and gain coefficients severally, we let $J_0(2\theta_0)=0$, so the DC component is independent of the magneto-optical modulation $I_{dc}=k_0I_0/2$. We obtain $2\theta_0=2.405$. By rotating analyzer, we let $\beta_1=22.5°+n\pi$, then $\cos2\beta_1=\sqrt{2}/2$, $\sin2\beta_1=\sqrt{2}/2$. Before putting into the test sample $\delta=0$, $\gamma=0$, $A_0=B_0=\sqrt{2}/2$, the measured fundamental frequency component is:

$$I_{1f0}=\frac{1}{2}k_1\cdot\sqrt{2}\,J_1(2\theta_0)I_0 \tag{11}$$

The second harmonic component is:

$$I_{2f0}=\frac{1}{2}k_2\cdot\sqrt{2}\,J_2(2\theta_0)I_0 \tag{12}$$

After putting into the test sample, the fundamental frequency component is:

$$I_{1f1}=\frac{1}{2}k_1\cdot 2B_1J_1(2\theta_0)I_0 \tag{13}$$

The second harmonic component is:

$$I_{2f1}=\frac{1}{2}k_2\cdot 2A_1J_2(2\theta_0)I_0 \tag{14}$$

Where:

$A_1=\sqrt{2}/2[(\cos^2 2\gamma+\cos\delta\sin^2 2\gamma)+(1-\cos\delta)\sin 2\gamma\cos 2\gamma]$,

$B_1=\sqrt{2}/2[(\sin^2 2\gamma+\cos\delta\cos^2 2\gamma)+(1-\cos\delta)\sin 2\gamma\cos 2\gamma]$

We rotate the analyzer continues, and let $\beta_2=-22.5°+n\pi$, then $\cos 2\beta_2=\sqrt{2}/2$, $\sin 2\beta_2=-\sqrt{2}/2$, the measured fundamental frequency component is:

$$I_{1f2}=\frac{1}{2}k_1\cdot 2B_2J_1(2\theta_0)I_0 \tag{15}$$

The second harmonic component is:

$$I_{2f2}=\frac{1}{2}k_2\cdot 2A_2J_2(2\theta_0)I_0 \tag{16}$$

Wherein:

$A_2=\sqrt{2}/2[(\cos^2 2\gamma+\cos\delta\sin^2 2\gamma)-(1-\cos\delta)\sin 2\gamma\cos 2\gamma]$,

$B_2=-\sqrt{2}/2[(\sin^2 2\gamma+\cos\delta\cos^2 2\gamma)-(1-\cos\delta)\sin 2\gamma\cos 2\gamma]$

By the formula (11), (13), (15), we can obtain:

$$M=\frac{I_{1f1}+I_{1f2}}{I_{1f0}}=\frac{k_1\cdot 2B_1J_1(2\theta_0)+k_1\cdot 2B_2J_1(2\theta_0)}{k_1\cdot\sqrt{2}\,J_1(2\theta_0)}=$$

$$\sqrt{2}(B_1+B_2)=(1-\cos\delta)\sin 4\gamma \tag{17}$$

$$N=\frac{I_{1f1}-I_{1f2}}{I_{1f0}}=\frac{k_1\cdot 2B_1J_1(2\theta_0)-k_1\cdot 2B_2J_1(2\theta_0)}{k_1\cdot\sqrt{2}\,J_1(2\theta_0)}=$$

$$\sqrt{2}(B_1-B_2)=\sin^2 2\gamma+\cos\delta\cos^2 2\gamma \tag{18}$$

By the formula (12), (14), (16), we can obtain:

$$Q=\frac{I_{2f1}+I_{2f2}}{I_{2f0}}=\frac{k_2\cdot 2A_1J_2(2\theta_0)+k_2\cdot 2A_2J_2(2\theta_0)}{k_2\cdot\sqrt{2}\,J_2(2\theta_0)}=$$

$$\sqrt{2}(A_1+A_2)=2(\cos^2 2\gamma+\cos\delta\sin^2 2\gamma) \tag{19}$$

As $\sin\delta\approx\delta$, by combining with the formula (17), (18), (19), we acquire the sample′s fast axis angle γ between P_1:

$$\gamma=\frac{1}{2}\arctan\frac{M}{2(1-N)} \tag{20}$$

The test glass sample′s stress birefringence is:

$$\delta_1=\delta\lambda/(2\pi l)\approx\lambda\sqrt{4-(Q+2N)}/(2\pi l) \tag{21}$$

Wherein, l is the thickness of the test sample.

It can be seen that we use the DC component to normalize the fundamental frequency component and second harmonic component combinablenably, the ratio eliminates the influence of the initial light intensity I_0, the photoelectric converter and gain factor k, that is to say it eliminates the impact on the measurement results of the source light intensity fluctuation and the circuit gain drift at the same time.

2 Experiment

The experimental apparatus is shown in Fig.2, the light source is a semiconductor laser in the wavelength of 550 nm with a collimating lens, the polarizer and analyzer are 20 mm×20 mm×20 mm specific Glan–Taylor prisms, and it′s light through area is Φ16 mm, the extinction ratio is 10^{-5}, the test sample is colorless premium k9 glass with smaller stress value, surface area of Φ40 mm and thickness of 4 mm, processed by the thermal annealing. The magnetic optical glass is selected from XIOPM production with higher Verdet constant, thickness of 40 mm, and is Φ20 mm. Around the outside of magnetic optical glass is metal coils,

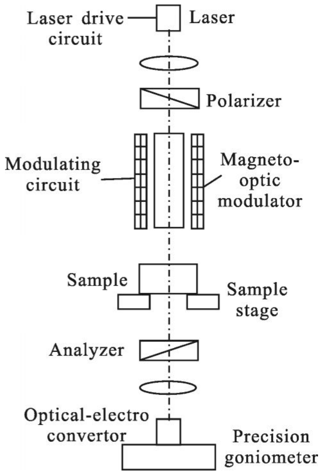

Fig.2 Experimental apparatus

we let alternating current passing it to generate a sinusoidal alternating magnetic field, a magnetic field with uniform strength and direction is formed on the built-in magneto-optical glass region. Using a photodiode detector, through preamplifier, filtering and the main amplifier, the light intensity of the detected signal by modulating the signal detected, the DC component is separated from the fundamental frequency and second harmonic components, and we enter them into the computer through the data acquisition card respectively. In the experimental process, before the sample is placed, we rotate analyzer in the extinction position relative to the polarizer, mark the position of the analyzer at this time, and we adjust the modulation angular amplitude of the magneto-optical modulator adjustment to zero, increase gradually from zero to let the measured DC component to a constant value, that is to say the DC component is independent of the magneto-optical modulator, then twice of the magneto-optical modulation angular amplitude are 2.405. Then we rotate the analyzer, its azimuth angle is $\beta_1=22.5°$ relative with the original azimuth. We register the intensity values of the respective components of the detection signal, and then put into the test sample, the respective components of the detection signal change due to the existence of sample internal stress, we record the detected value and store it in the computer, we rotate the analyzer continue in the reverse direction, let its azimuth angle $\beta_2=-22.5°$ relative with the original azimuth, we detect the signal $I_{1/2}$, $I_{2/2}$, according to the formula (17), (18), (19), we operate each measured value, and translate glass sample to be measured repeatedly, and by the formula (20), (21), we calculate the internal stress and the stress birefringence detected value at the center of the area and the deviation from the center region of 5 mm, 10 mm, 15 mm all around the four positions of the test sample, the values are shown in Tab.1.

Tab.1 Experimental data

Position/mm	$\gamma/(°)$	$\delta_l/\mathrm{nm\cdot cm^{-1}}$
The center 0	122°6′42″	12.5
Up 5	123°2′5″	13.0
Down 5	122°10′41″	14.7
Light 5	122°3′59″	13.6
Righ 5	122°9′43″	12.9
Up 10	125°2′47″	14.0
Down 10	122°23′49″	15.7
Light 10	122°25′7″	14.0
Right 10	122°6′9″	13.8
Up 15	125°2′40″	11.8
Down 15	123°3′9″	15.7
Light 15	122°5′7″	15.0
Right 15	122°10′13″	14.0

From the above data we see that, the internal stress direction measurement accuracy is up to 5 seconds in the glass internal stress measurement system with the magneto-optical modulation method, stress birefringence measurement accuracy is up to 0.5 nm/cm. From the stress data shown in Tab.1, we can determine the quality of the sample glass is good or bad at the same time, thus guide annealing and processing of glass productions further according to the measured results.

3 Conclusion

A magneto-optical modulation method for measuring the internal stress in the glass is raised in this paper, which uses the magnetic rotation effect of magneto-optical glasses, affecting the signal beam with the sinusoidal alternating magneto-optical modulation, and by demodulating the detected signal, it eliminated the effect to the measurement results of light source intensity fluctuations and circuit gain drift, achieved the direction of the internal stress of the tested glass samples and the size of the stress birefringence. The effectiveness of the method was found through theoretical analysis and experimental verification, the measurement method accuracy of the stress direction within the glass is 5 seconds, and the stress birefringence measurement accuracy is 0.5 nm/cm. The purpose of internal stress measurement is to feedback to the glass production stage in order to develop a more reasonable basis, which is to provide for taking more suitable heat treatment equipment and heat treatment process of glass annealing, and guidance glass processing production of the products. With the use of glass in the field of national defense and civil applications becomes more and more widespread, the requirements of its internal stress measurement accuracy are increasing, the proposed method raised in this article has important guiding values for glass annealing and application.

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