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Study on force distribution of the tempered glass based on laser interference technology

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ABSTRACT

The force distribution of inside the tempered glass is detected by the Mach–Zehnder interferometer. In the experiment, the interference fringes are captured by a CCD camera, filtered in frequency domain, and the tempered glass real phase distribution is obtained by utilizing branch-cut algorithm for phase unwrapping. The tempered glass internal force distribution can be derived by means of the relationship between phase distribution and external force. The results demonstrated that the force distribution is almost linear in direction to parallel the external pressure; although some fluctuations appear to be perpendicular to the external pressure, the overall change is smaller.

1. Introduction

Since the advent of laser in the 1960s, interferometric technique presents its diversity and has achieved rapid development, among which the main techniques are laser heterodyne interferometry, laser holographic interferometry, laser speckle interferometry, single and double frequency laser interferometer, and multi-beam interferometry, etc. Due to its characteristics of non-contact and high precision, it has been extensively applied in the field of non-destructive testing. In recent years, Tian et al. used interferometry to detect the accurate measurement of aspheric lenses and spherical radius [1–3]. Cui Yanjun and Yang Zhenyu et al. used the laser interferometer to accurately test the displacement [4,5]. Song Song et al. studied the measurement of small vibrations [6]. Lü Qieni et al. studied particle imaging by using laser interferometer [7]. The interferometric technique can also be applied to a wide range of measurements of the deformation, thickness, density, and refractive index, etc. [8–13].

That tempered glass is widely used in daily life, for example, in the automotive industry and the construction industry, mainly because of its high security. In order to make more extensive application of high quality tempered glasses, security detection has to be done. In this paper, test system of digital images has been set up through the Mach–Zehnder interferometer systems and CCD image pickup device. To restore the phase of the tempered glass, the collected interference images are digitized by spatial-carrier Fourier transform method, contributing to obtain the force distribution of the tempered glass under the external force of 20 N. This article is the first application of the laser interferometer in the field of glass detection, which will open a new way for the detection of tempered glass.

2. Basic theory

2.1. Basic principles of Fourier transform of interfere images

By the and after meeting the interference condition, the light intensity distribution of the interference fringe image can be expressed as [14]:

$$G(x, y) = a(x, y) + b(x, y)\cos(\phi(x, y)) \qquad (1)$$

where $a(x, y)$ is the background light intensity distribution of the interference fringe, $b(x, y)$ is the contrast of the stripes; $a(x, y)$ and $b(x, y)$ are unknown variables; $\varphi(x, y) = \varphi_s(x, y) - \varphi_r(x, y)$ is the phase distribution difference; $\varphi_s(x, y)$ is the phase of the measured beams and $\varphi_r(x, y)$ is the phase of the reference beams. In formula (1), there are three unknown numbers and the phase difference $\varphi(x, y)$ cannot be solved. Therefore, in order to solve $\varphi(x, y)$, we introduce spatial carrier frequency of $f = f_x x + f_y y$, in which f_x and f_y are the carrier frequencies in the direction of x and y, meaning to change

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the inclination angle of the test surface and the reference surface, so that the reference wave would be inclined and the fringes on the interference map would be denser in the direction of x and y. The formula of the light intensity on the interference fringe image becomes as the follow:

$$\begin{aligned} G(x,y) &= a(x,y) + b(x,y)\cos[2\pi f + \phi(x,y)] \\ &= a(x,y) + b(x,y)\cos[2\pi(f_x x + f_y y) + \phi(x,y)] \end{aligned} \tag{2}$$

f: the spatial carrier frequency; $f = 1/T$, T: the space cycle of interference fringes.

The complex form of formula (2) is,

$$\begin{aligned} G(x,y) &= a(x,y) + c(x,y)\exp(i2\pi f_x x + i2\pi f_y y) \\ &\quad + c^*(x,y)\exp(-i2\pi f_x x - i2\pi f_y y)] \end{aligned} \tag{3}$$

where $c(x,y) = \frac{1}{2}b(x,y)\exp(i\phi(x,y))$

Conducted the two-dimensional Fourier transform of spatial variables in formula (3), the following relations can be obtained:

$$G_0(f_1,f_2) = A(f_1,f_2) + C(f_1 - f_x, f_2 - f_y) + C^*(f_1 + f_x, f_2 + f_y) \tag{4}$$

$C(f_1 - f_x, f_2 - f_y)$: the positive first-level spectrum division, $C^*(f_1 + f_x, f_2 + f_y)$: the negative first-level spectrum division, $A(f_1, f_2)$: the zero level spectrum division.

Fig. 1(a) shows the spectrum of the background light intensity of the interference image.

The appropriate filter is selected, the positive first level spectrum is separated and moved to the original point to obtain formula $C(f_1, f_2)$, which is showed in Fig. 1(b). Fig. 2(a) and (b) are the interference fringes and three-dimensional Fourier spectrum distribution collected in the experiment.

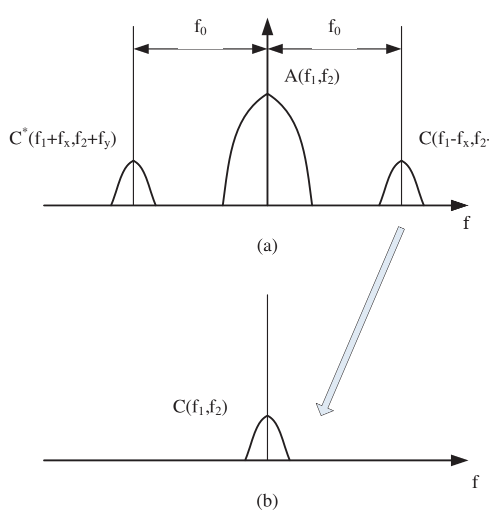

Fig. 1. The action of filter.

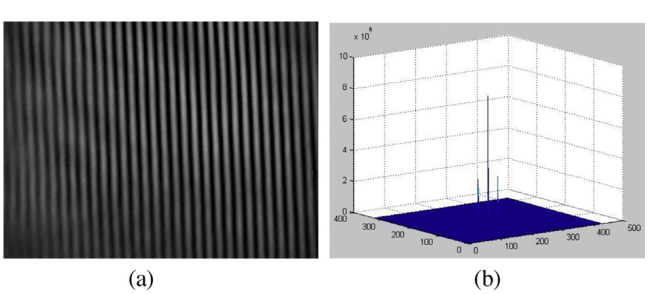

Fig. 2. (a) Interference fringe map of the tempered glass. (b) Three-dimensional Fourier spectrum.

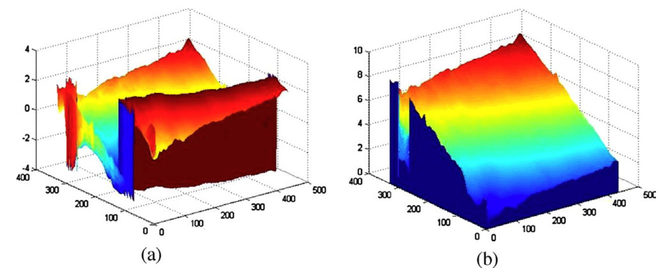

Fig. 3. The phase map.

A two-dimensional inverse Fourier transform is:

$$F^{-1}[C(f_1,f_2)] = c(x,y) = \frac{1}{2}b(x,y)\exp[i\phi(x,y)] \tag{5}$$

$$\phi(x,y) = \tan^{-1}\frac{Im[c(x,y)]}{Re[c(x,y)]} \tag{6}$$

where $\mathrm{Im}[c(x,y)]$ and $\mathrm{Re}[c(x,y)]$ are the respective imaginary part and the real part of $c(x,y)$ respectively.

2.2. Phase unwrapping

Since trigonometric is cyclical, phase is wrapped in the main value of the arc tangent function and the phase value is also extended between $[-\pi,+\pi]$ when the computer is processing arc tangent function in the digital interference images. When the real phase is beyond $[-\pi,+\pi]$ and under the modulating effects of trigonometric, wrapped phase distribution $[-\pi,+\pi]$ is formed, and the image of computer processed wrapped phase maps of the tempered glass is showed in Fig. 3(a). In this paper, Goldstein's branch-cut unwrapping algorithm is applied to get the real phase of the tempered glass.

Goldstein's branch cut follows a specific algorithm: search the residual handicap of the entire wrapped phase image, establish 3×3 windows at the first residual handicap, and then search the next residual handicap. Whether the searched residual is of the same polarity, it is connected to the first residue. If the two residuals are of the opposite polarity, they are called the residual polar balance of the connected branches. If they are of the same polarity, the search window continues to find a new residual handicap, and connect at the center of the windows regardless of whether the residue was connected with other residues or not. If one residual is not connected with others, the polarity would be added to the residue to which it is connected, otherwise the accumulation is not needed. If the accumulated polarity is of imbalance, and the window has completed the search, a new window is supposed to be set with the next residual handicap as the center and continues the next round of search. If the accumulated polarity is still of imbalance, the windows are to be extended to 5×5 and continue the search by using the steps above until the windows extend to the border of the image. In the end, sticks tangent is generated by the connection between the residues and the boundary and then integrate along the path of the sticks tangent.

2.3. Model establishment of phase and force distribution

As Fig. 4 shows, the forced tempered glass is perpendicular to axis Z. The phase will change when the light through the glass phase. Assuming the external force is F (directing along the axis Y), and the glass thickness remains unchanged. The changes in density of tempered glass by the force cause the changes in refraction and hence, the phase also be changed. To analyze the relationship between $F(x,y)$, the force at any point within the glass, and $\Delta p(x, y)$, the amount of phase change, set the light wavelength to be λ,