Moiré Deflectometer for measuring distortion in sheet glasses

Saifollah Rasouli [a1] and Mohammad Taghi Tavassoly [a,b]

[a] Institute for Advanced Studies in Basic Sciences, Zanjan, Iran, P.O.Box: 45195-1159 ;
[b] Physics Department, Tehran University, Tehran, Iran.

ABSTRACT

In glass casting or shaping processes, some times wavy and distortion defects are developed in glass sheets. Specifying the locations of these defects and measuring the deflections they cause are significant parameters in many applications. There are several techniques for observing and measuring these defects, but the technique we introduce in this work is more simple and flexible and can be easy installed in production line for quality controlling purposes. The presented deflectometer functions in the following way. The imaging system of the device forms an image of large-scale low frequency linear periodical pattern painted on a vertical plane on a transmission grating. The distance between the object grating (painted pattern) and the second grating is so that the frequencies of the image grating and the second (probe) grating are practically the same. There is a small angle between the lines of the latter gratings to form moiré fringes. A CCD camera transfers the moiré fringes to a PC. By applying phase shifting technique, which is realized by shifting the probe grating in definite steps in its plane in a direction perpendicular to its lines, the phase distribution due to imprecations in optical system and gratings, are specified, At this stage the defected sheet glass is installed between the object grating and the imaging system and the distorted moiré pattern is processed as described before. The difference between two-phase distributions is the phase distribution caused by the defects in the glass, which can be easily converted into the required ray deflections. All the processes are carried out automatically in a time less than 30 seconds and the accuracy of the measurement is of the order of 20 arc seconds.

Keywords: moiré technique, phase shifting, deflectometry, defect measurement

1. INTRODUCTION

Optical distortion is defined as local variation of optical deviation, which results in distortion of the image perceived on viewing through the panel. Thus, straight lines appear crooked or curved.

Measurement of distortion in sheet glasses, like car windows, is a vital issue in standard institutes. Several visual and optical techniques are available for this kind of measurinents[1,2]. Among the visual techniques the Zebra test is more frequently is applied. This technique involves measuring distortion by placing the glass sample between the viewer and a diagonally striped (Zebra) examining screen. The glass is placed on a vertical plane with the principal distortion running in a vertical direction. Optical irregularities in the glass then causes the normally regular and parallel lines of zebra board to become distorted. The glass is rotated about a vertical axis until these Zebra line distortions are on the verge of disappearance. The rotated angle is a measure of the distortion of the glass. This technique and other techniques like lines strip projection technique and Hartman technique heavily depend on the observer skill, take more time and precision is low.

In this work we apply moiré technique and phase shifting method to measure distortion and deflection angle in sheet glasses. The technique can be applied in very short time and it specifies distortion on entire sample with high precision.

2. THEORETICAL APPROACH

In Fig.1 the image of the object grating $G1$ is projected by the imaging system I.S. onto grating $G2$. When the defected glass $Gl.$ is installed at distance ℓ from $G1$, it deflects the ray at the defected point M by an angle α, which satisfies the following equation

$$\delta\xi \cong l\alpha , \tag{1}$$

[1]Corresponding Author: Saifollah Rasouli, Email: rasouli@iasbs.ac.ir, Fax: +98-241-415-2104

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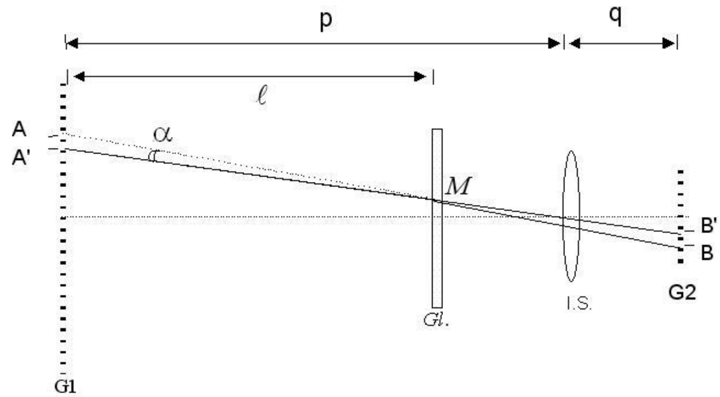

Figure 1. Schematic diagram for describing the working principles. $G1, Gl.$, $I.S.$ and $G2$ stand for the linear periodic reflectance pattern, sample sheet glass, imaging system, and probe grating, respectively.

where $\delta\xi = AA'$ is apparent displaced distance on $G1$. The corresponding displacement on the image plane, $G2$, is given by

$$\delta\eta = \frac{q}{p} l\alpha, \tag{2}$$

where the ratio q/p is the linear magnification of the imaging system. Considering that $\delta\eta$ is the local displacement of the lines of the image grating it can be related to the moiré fringe displacement by the following formula[3]

$$\frac{\delta\eta}{q_2} = \frac{\delta q_m}{q_m}, \tag{3}$$

where q_2 and q_m stand for the pitches of grating $G2$ and the moiré pattern, respectively. Substituting from Eq. (3) in Eq. (2) we get

$$\alpha = \frac{pq_2}{q\ell}\frac{\delta q_m}{q_m}. \tag{4}$$

But, the moiré fringe displacement δq_m can be expressed in terms of phase change $\delta\phi$ by the following equation

$$\delta q_m = \frac{q_m}{2\pi}\delta\phi. \tag{5}$$

Substituting form Eq. (5) in Eq. (4) we get

$$\alpha = \frac{pq_2}{2\pi q\ell}\delta\phi. \tag{6}$$

Thus, by specifying the phase change $\delta\phi$ caused by the sheet glass, Eq. (6) provides the ray deflection angle.

3. PHASE EVALUATION TECHNIQUE

Automatic fringe analysis is an important tool for deriving a precise phase map from fringe pattern. Now a day it is extensively used in industry for evaluation and inspection of optical components and devices.

There are two widely used methods for automatic phase evaluation, namely, phase shifting and Fourier transforms methods. The former is used more frequently because it does not require fully periodical fringe pattern. This technique require at least three phase shifted fringe patterns which are generated sequentially by appropriate phase-shifts[4,5].

Our analysis is based on the delivery of four phase-shifted moiré patterns in parallel to PC for phase evaluation [6]. Figure 2 shows a conceptual illustration of the analysis. From four phase-shifted moiré-patterns Fig. 2-a, the wrapped phase map is derived, Fig. 2-b, then, by unwrapping the latter phase distribution is obtained Fig. 2-c.

Introduction of a high-frequency spatial carrier into the pattern to be evaluated provides a phase-modulated carrier, whose demodulation is realized by overlapping it on a transmission grating located outside the optical module, which supplies the fringe pattern. In this case, an output intensity distribution equal to the product of the phase-modulated carrier intensity and the corresponding transmission function is observed. In order to re-image this multiplicative moiré pattern in the detector, a diffusing screen is placed just behind the transmission grating. The lowest frequency pattern (i.e. the moiré image) is usually selected using a low-pass-filtering process. The phase of moiré image contains the original phase ϕ, a linear phase term, and an additional phase term proportional to the in plane displacement of the probe grating. By acquiring a series of moiré images with various additional phase terms, one can apply a standard phase stepped interferometry (PSI).

This method contemplates the possibility that the fringe profile is non-sinusoidal nature. Moreover, the modulator can be located outside the optical module, which provides the fringe patterns, thus improving the measurement-process stability.

The four-step algorithm requires that the four separate moiré patterns of the part under test to be recorded and digitized. A 90^{o} optical phase-shift is introduced into the probe grating between each of the sequentially recorded a moiré pattern.

The ultimate phase distribution could be derived form these moiré patterns by application of the following formula to each pixel[4]:

$$\phi(x, y) = \tan^{-1}\left(\frac{I_2 - I_4}{I_1 - I_3}\right) \cdot \tag{7}$$

The phase distribution can also be calculated quickly with a look up table implemented in read only memory.

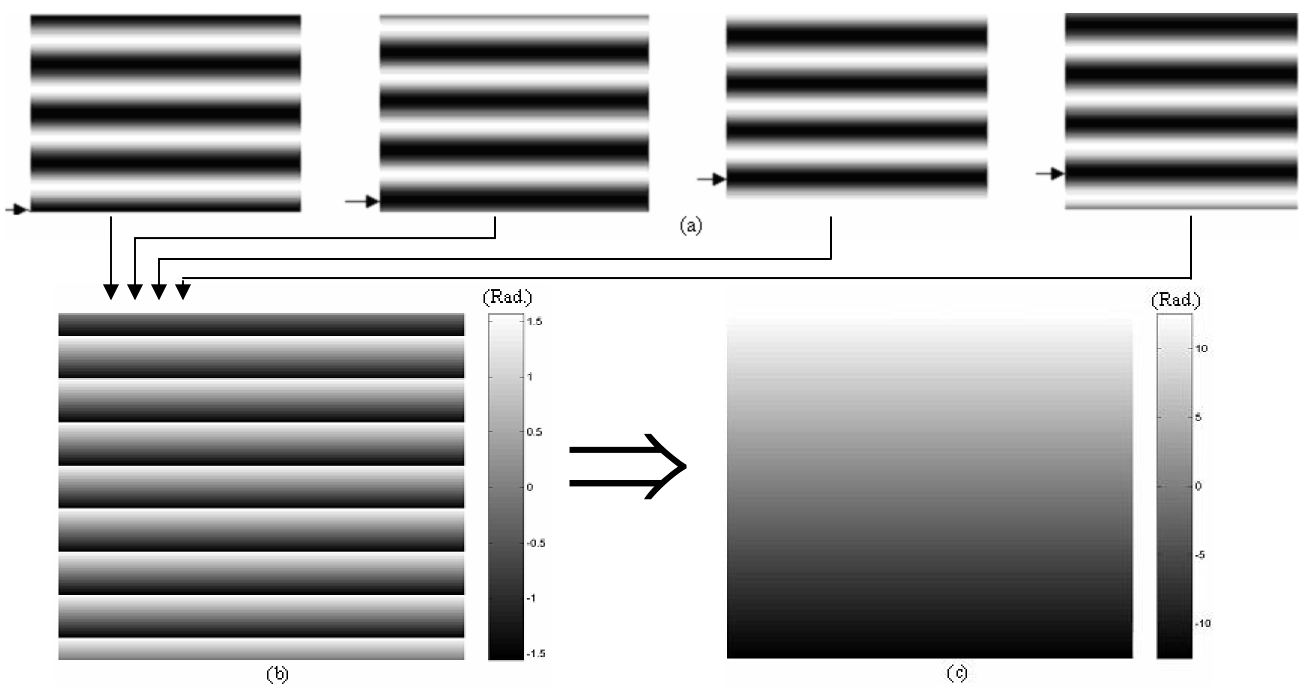

Figure 2. Schematic diagram of real-time fringe analyzer based on phase-shifting moiré-pattern technique. From four phase-shifted moiré-patterns, Fig. 2-a, the wrapped phase map is derived, Fig. 2-b. By unwrapping the latter, the phase distribution is derived Fig. 2-c.

3.1. Phase Unwrapping

Owing to the multiple value of the inverse trigonometric function employed to calculate the phase ϕ in the majority of the phase-evaluation methods (PEMs), these usually provide the phase ϕ value modulo π. However, it is possible to identify the quadrant where the phase ϕ is located if the signs of the corresponding argument are taken into account. These PEMs therefore provide phase ϕ values in the range $[0,2\pi)$ rad., the so-called principal values. In this way, the obtained results exhibit a discontinuity every time the phase ϕ increases or decreases by 2π rad. with respect to a certain arbitrary phase origin. These discontinuities need to be resolved, to obtain continuous values of the phase ϕ. This process is called phase unwrapping and it is a trivial process, as long as the patterns are continuous, sampled with high enough density and presents a good signal-to-noise ratio. In such a case, the process is carried out by adding (or subtracting) 2π rad. every time a discontinuity is detected in the principal phase ϕ values, in order to get the unwrapped phase map. (Figure 2-c).

In our calculations the PSI techniques recover phase values using an arctangent function. Such calculation will only provide phase module π. Thus, the resulting values lie between $-\pi/2$ and $\pi/2$ rads and referred to as wrapped phase values (figure 2-c).

4. EXPERIMENTAL PROCEDURES AND RESULTS

Schematic diagram of the moiré deflectometer is shown in Fig. 3. It consists of carrier grating $G1$, imagining system $I.S.$, stepper motor system SM, image grabber and a PC. The imagining system, $I.S.$, consists of transmission grating $G2$, diffuser screen S and secondary imaging lens L. The stepper motor, which runs by parallel port output, realizes the phase-shifting process. Also unwrapping is implemented by software, which is written in Matlab language. The software is menu-driven and includes Graphical User Interfaces (GUI) for the user interaction.

To test a glass sheet, first we determine the phase distribution in the testing field in the absence of the glass sheet. Figs 4-a, 4-b, 4-c show the moiré pattern, wrapped phase-maps, and unwrapped phase-map of the field, respectively. The corresponding images at presence of the sheet glass are shown in Figs 5-a, 5-b and 5-c. The deflection angle distribution on the map of the glass sheet in terms of arc minutes (in gray bar) is shown In Fig. 6.

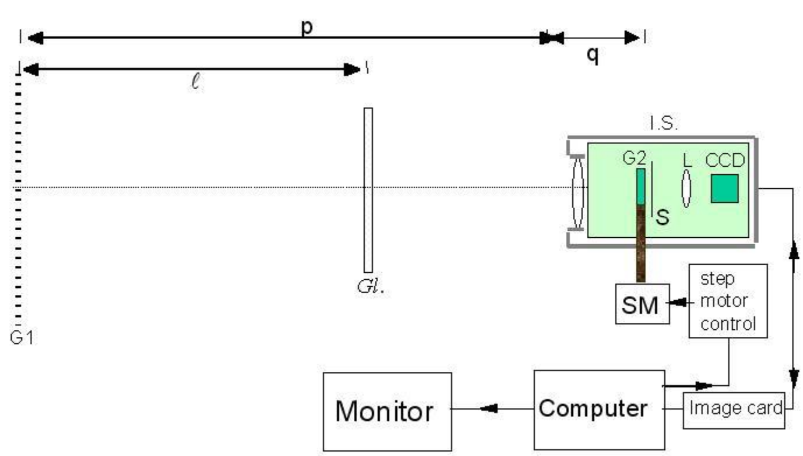

Figure 3. Schematic diagram of moiré deflectometer for specifying light deflection distribution in sheet glasses. $G1, Gl.$, $I.S.$ and SM stand for the linear periodic reflectance pattern, sample sheet glass, imaging system and stepper motor, respectively. The imagining system, $I.S.$, consists of transmission grating $G2$, diffuser S and secondary imaging lens L.

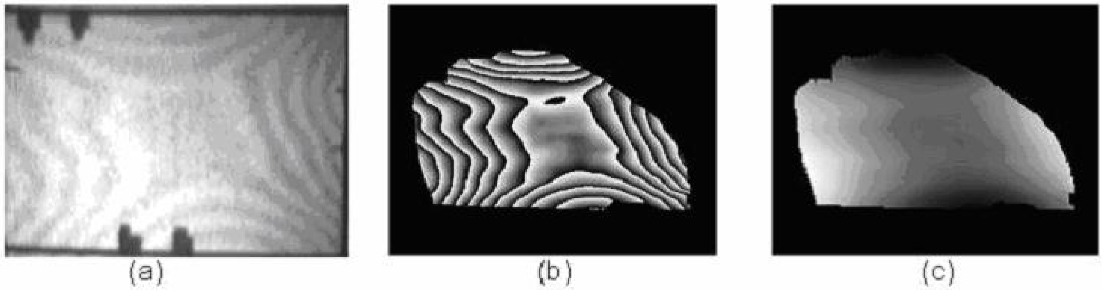

Figure 4. The moiré pattern, (a), the wrapped phase-map, (b), and the corresponding unwrapped phase-map, (c), of the testing field in the absence of the sample.

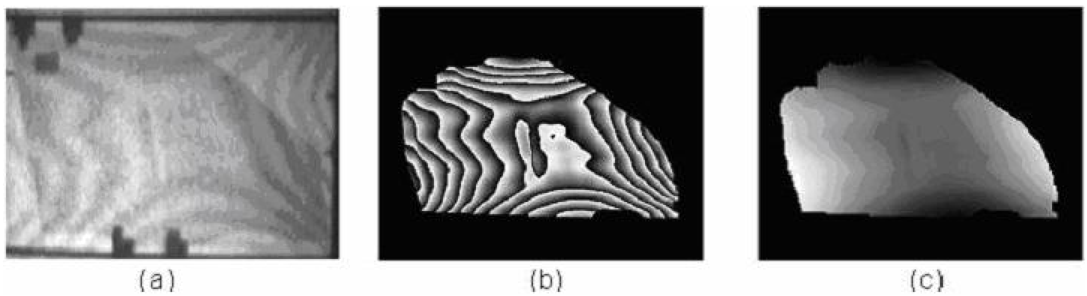

Figure 5. The moiré pattern, (a), the wrapped phase-map, (b), and the corresponding unwrapped phase-map, (c), of the field at the presence of the sample (defected glass sheet).

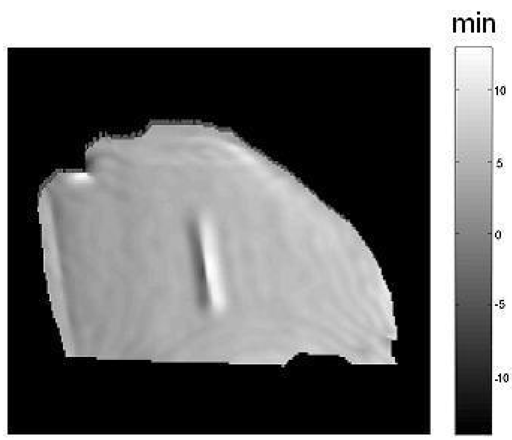

Figure 6. The deflection angle distribution on the map of the glass sheet (defected glass sheet) in terms of arc minutes shown as gray bar

5. CONCLUDING REMARKS

The presented technique is simple and powerful technique for measuring distortion in sheet glasses and windows. It can provide the light deflection angle distribution on the entire map of the glass sheet by 20arc second precision.

In this method when a beam of light passes through the sample, we can detect the deflection projects ray in direction perpendicular to the carrier grating lines. To detect the other defection components we rotate the gratings in vertical plane by 90^o we can get other component of deflected light. In other word we can get the sagittal and the meridional deflections of the beam on the entire map of the sample.

By choosing suitable size carrier grating, very wide range of glasses sizes can be tested. Also by reducing the distance between sample and imaging system one can improve the precision of the measurement. The presented deflectometer is full automatic and can be installed in production line.

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