Automatic wavefront measurement technique using a computer display and a charge-coupled device camera

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Abstract. A simple and fully automated technique for wavefront measurement is presented. This technique is based on the use of a computer display (for example, a CRT or a thin film transistor (TFT) monitor) to generate intensity-modulated patterns from which images are taken by a CCD camera. When a phase object is located between the display and the camera, the intensity patterns are distorted. By measuring this distortion, the gradients of the phase change caused by the object can be obtained. To simplify the data analysis it is practical to display on the monitor a grating with a sinusoidal intensity profile, which enables the use of standard fringe pattern analysis techniques. We use phase-shifting and temporal phase-unwrapping techniques. The use of a computer display for fringe (or grating) generation leads to the possibility of adjusting the sensibility of the measurement in function of the phase variation of the object to test and avoiding the problems of having a fixed grating period (as in the case of Ronchi rulings or printed gratings) or using mechanical parts to change them. Experimental measurements of two different ophthalmic lenses with local distributions of focal lengths prove the versatility of this method for optical testing. The method is simple, flexible, and low cost, yet it yields a remarkably high SNR. Compared with other techniques such as interferometry and moiré deflectometry, the setup is cheaper and far easier to align. [DOI: 10.1117/1.1459055]

Subject terms: wavefront measurement; phase shift; phase gradient; ophthalmic lens; moiré deflectometry; phase unwrapping.

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1 Introduction

Many methods for wavefront measurement have been presented in the literature. These methods can be grouped according to different classifications, as, for example, whether they require coherent or incoherent illumination. Another classification can be made depending on whether they measure the phase directly or estimate it from the measurement of the first or second derivative (i.e., the slope or the curvature) of the wavefront.

Almost all interferometers[1] (e.g., Michelson, Fizeau, Twiymann-Green) provide a direct measurement of the wavefront phase deviation with respect to some reference, requiring coherent illumination and a stable mechanical system. Moiré deflectometry[2,3] and Ronchi and Hartmann tests[1] obtain the wavefront from the local slopes components (or gradients), improving the SNR of the measurement. Most of these methods require coherent illumination and a precise alignment and positioning of the optical elements.

Recently, Massig[4] proposed a new simple technique for measuring the wavefront slopes. The basic idea of this setup is to image a printed fringe pattern in a CCD camera, while a phase object is placed on the ray path. The deflections introduced by the test object modify the reference fringe pattern, and by evaluating the images with the Fourier transform method, the wavefront slopes can be obtained. As the fringe pattern used by Massig is periodic along one dimension, only one component of the wavefront slope can be measured at a time. For that reason, Perciante and Ferrari[5] developed a method that enables the visualization of two wavefront slope components, by printing a 2-D periodic fringe pattern. In both works, the sensibility of the method is fixed because it depends on the period of the printed patterns.

Here, we extend these ideas, by replacing the fixed printed pattern by a computer image display, like a CRT monitor or a TFT flat panel display. In this way, it is possible to change the characteristics of the displayed patterns in real time, enabling us to (1) obtain more precision by displacing numerically the fringe pattern and using phase shifting methods, (2) obtain the desired wavefront slope components by adjusting the fringes orientation angle without using mechanical parts, and (3) modify the sensibility of the method by changing the period of the fringe pattern. This last characteristic is very attractive because it permits the utilization of temporal phase unwrapping (TPU) methods,[6] enabling the complete automation of the measurement process and avoiding the utilization of more complicated unwrapping algorithms.

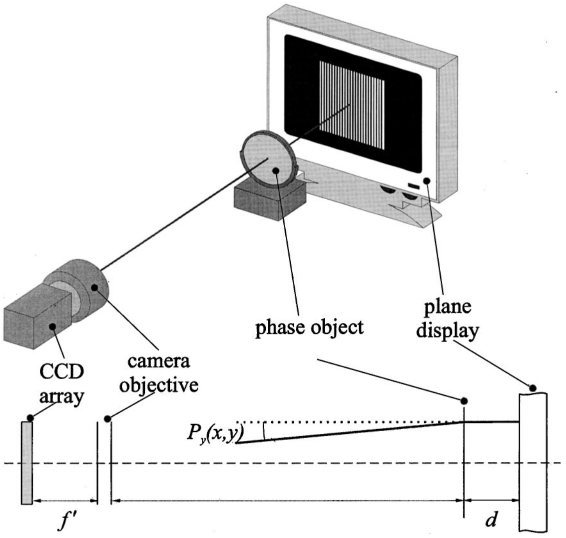

Fig. 1 Schematic of the experimental setup.

Fig. 2 Fringe pattern obtained with the progressive lens placed at 10.0 mm from the screen.

2 Principle and Experiment

The experimental arrangement is shown in Fig. 1. The CCD camera is focused on the screen surface and a periodic pattern is displayed on it. Let us assume, without loss of generality, that the displayed pattern is oriented along the vertical axis. The irradiance distribution on the camera $I_0(x,y)$ is given by

$$I_0(x,y)=a+b\cos\left(\frac{2\pi}{p}x\right), \tag{1}$$

where a is the offset, b is the amplitude modulation, p is the fringe period of the pattern, and x and y are the coordinate system axes measured at the screen. When the phase object is positioned on the optical path, the rays that pass through the object are deflected, changing the image of the fringe pattern on the CCD. The new irradiance distribution $I(x,y)$ is given by

$$I(x,y)=a+b\cos\left[\frac{2\pi}{p}x+\phi(x,y)\right], \tag{2}$$

where $\phi(x,y)$ is the phase variation of the fringe pattern digitized by the CCD camera, caused by the presence of the phase object.

The rays refracting at a point (x,y) on the phase object plane, will be deviated with angles P_x and P_y. Let us assume that these angles are small and the distance from the phase object to the screen d is much smaller than the distance from the screen to the camera. Looking toward the screen from the center of the pupil of the camera lens, the effect of the local deviations is that the point (x,y) on the screen display is displaced by the distances $\mathrm{d}P_x$ and $\mathrm{d}P_y$ along the horizontal and vertical directions, respectively. As the pattern is oriented along the vertical axis, only the horizontal displacement is detected, producing a phase change given by[4]

$$\phi(x,y)\cong\frac{2\pi d}{p}P_x(x,y). \tag{3}$$

Therefore, from the phase of the fringe patterns recorded by the camera it is possible to obtain a direct estimation of the wavefront slopes. It is clear that the sensitivity of the measurement is proportional to the ratio d/p. Consequently, to obtain the best accuracy this ratio must be maximized. However, an upper limit for this ratio is imposed by the fact that the fringe pattern recorded on the camera must be adequately sampled (at least at two points per cycle). As the sensitivity depends on two different parameters, we have more freedom to adjust the measurement range to the particular characteristics of the object to test.

3 Experimental Setup

To show the method execution, we implemented an experimental setup to test optical components, particularly ophthalmic lenses. The camera is a digital CCD with 752×494 pixels with an 8-bit analog-to-digital (A/D) converter. The display used is a 15-in. TFT desktop monitor configured at a resolution of 1028×764 pixels with a vertical refresh rate of 60 Hz and a square pixel of 0.3 mm by side. Although not shown in this paper, initially we used a standard CRT monitor, with a nonflat screen. This introduces a measurement error because the distance d is not constant, and causes a small curvature in the reference fringe pattern. Although these errors could be considered and corrected by software, we think that using a flat panel display is a simple and more accurate solution.

Diverse optical components with different characteristics can be analyzed with this technique. Two examples are shown in this paper. The first one is a progressive ophthalmic lens chosen by its high and continuous focal length variation (from infinity to around 0.4 m). Its lack of revolution symmetry permits to distinguish without difficulty the two components of the wavefront slope. The second example is a bifocal lens that has two well-defined zones with different focal length. In this example, the ability of the proposed method to deal with the discontinuity zones is

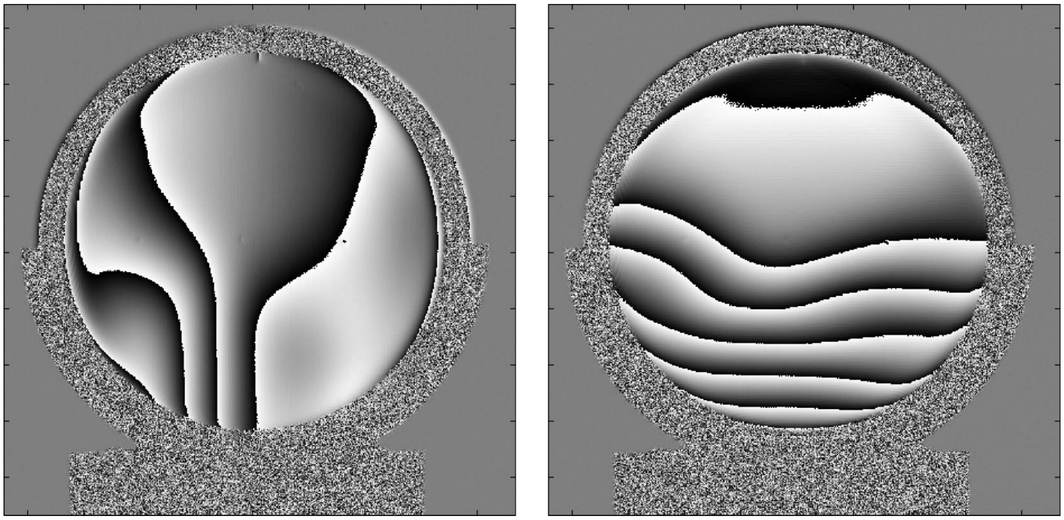

Fig. 3 Phase map differences obtained with fringe orientations: (a) vertical (as in Fig. 2) and (b) horizontal.

demonstrated. In both examples, the distance d between the lens and the display, was set to 100 mm, while the distance from the camera to the display is approximately 1800 mm.

We generate a grating with sinusoidal intensity profile in the computer memory, and display it on the TFT monitor. The grating sampling is of 6 points per cycle, which corresponds to a period of 1.8 mm on the monitor. The reference image (a image without object) is acquired, being useful to evaluate and correct the imperfections or misalignment of the fringe patterns displayed on the monitor. When the progressive lens is introduced in the optical path, the grating lines are deformed, as shown in Fig. 2.

4 Data Processing

To recover the phase encoded on the recorded patterns we can use any phase recovery method like the Fourier or the phase-shifting methods. The first one results in faster acquisition times, because only one image is required. However, we prefer to use the well-known four-bucket (three-step) phase-shifting algorithm because it enables us to obtain better measurement precision.

The phase difference between the object and reference phases reveals the light deviations caused by the object (see Fig. 3). Each phase map enables us to obtain the phase slope component orthogonal to the direction of the reference fringe pattern displayed on the monitor.

As the calculated phase values are wrapped onto the range $(-\pi$ to $\pi]$, phase unwrapping (restoration of the unknown multiple of 2π to all pixels) must be carried out before absolute ray deflection information can be deduced from the phase distribution. The normal methods for phase unwrapping involve a spatial comparison of phase values at neighboring pixels.[7,8] Thus, boundaries and regions with poor SNRs can adversely influence good data points. To

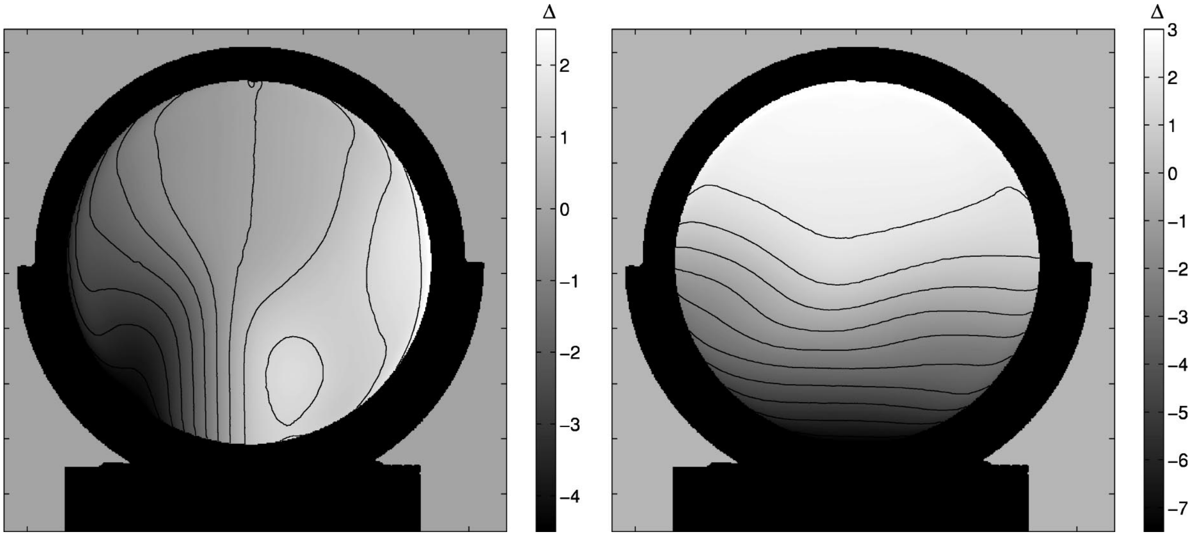

Fig. 4 Ray deviations (phase change gradients) of the progressive lens tested: (a) horizontal and (b) vertical components.

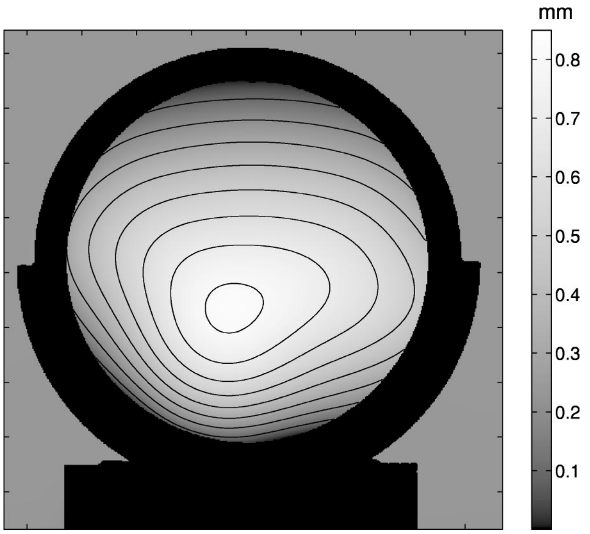

Fig. 5 Phase change caused by the progressive lens, obtained by integration of the phase gradients of Fig. 4.

avoid these problems we used a TPU method, where the phase at each pixel is measured in function of time, and the unwrapping is carried out along the time axis for each pixel independently of the others.[6]

All TPU algorithms need at least two phase maps with different multiplicative factor (sensibilities). As shown in Eq. (3), by changing the period of the fringe pattern displayed in the monitor, it is possible to change the sensibility of the measurement in this setup.

We employed a simple version of the TPU method described by Zhao et al.,[9] in which just two phase maps are required: one with a sensibility sufficiently low that all the unwrapped phase values lie within the range $(-\pi, \pi]$, and the other with a much higher sensibility that gives the finer precision of the measurement. The first map is then used to unwrap the second one.

By scaling the unwrapped phase maps according to Eq. (3), we obtain the wavefront slope components, as depicted in Fig. 4. The unit used for this representation, the prismatic diopter Δ, is usually employed in the ophthalmic practice and corresponds to a deviation of 1 cm in 1 m $(\approx 0.01\ \text{rad})$. To evaluate the measurement errors present in these results, we evaluate the standard deviation (σ) on a plane zone of the wavefront slope, obtaining a value of $\sigma \approx 0.0064\Delta$.

Once two components of the ray deflection are obtained, it is possible to estimate the wavefront emerging from the lens. In fact, we measured the directions of the refracted rays, which correspond to the directions normal to the wavefront W. If the curvature of this wavefront is not too large, the next relations hold[10]:

$$P_x=\frac{\partial W}{\partial x},\quad P_y=\frac{\partial W}{\partial y}, \tag{4}$$

where P_x and P_y are the components of the ray deflections shown in Fig. 4. Therefore, numerical integration of the ray deflection provides an estimation of the phase deviation introduced by the object. Figure 5 shows the phase change introduced by the progressive lens, obtained by integration of the wavefront slopes depicted in Fig. 4. The integration was performed with an algorithm based on multigrid techniques.[8] Note that the integration provides the wavefront except from a constant, so to obtain an absolute measurement it is necessary to know the absolute phase retardation in at least one point of the lens.

As explained before, one benefit of using a computer programmable display as a grating generator is that we are able to properly process objects with discontinuities in their phase profile. To illustrate this, Fig. 6 shows the maps obtained by testing the bifocal lens depicted before.

The phase slopes measured for both lenses were compared with the results obtained by two different methods: a moiré deflectometer using crossed gratings[2] and a direct

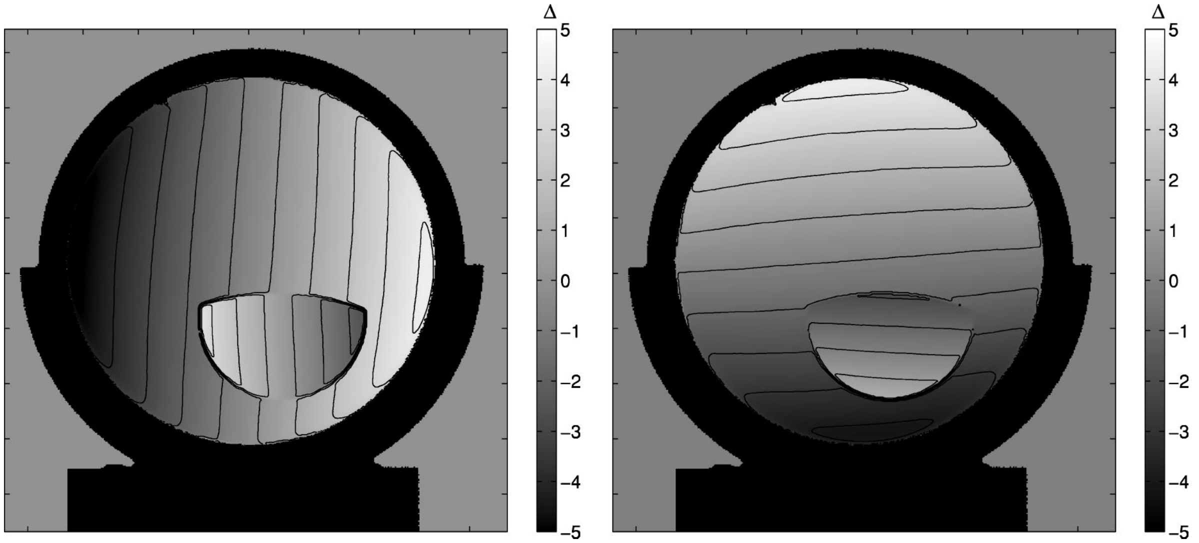

Fig. 6 Ray deviations (phase change gradients) of the bifocal lens tested: (a) horizontal and (b) vertical components.

laser beam deflectometry technique.[11] For these comparisons, it was necessary to adjust the spatial scale and position of the images obtained on the different experiments. After these adjustments, the comparison shows a good agreement (the differences are less than 5%).

5 Conclusions

We presented a simple and low-cost technique for measuring the wavefront change caused by a test object. The experimental setup consists of a computer monitor that displays fringe patterns and a CCD camera for recording them. Compared with other techniques like interferometry and moiré deflectometry, the proposed setup is cheaper, easier to align, and does not require coherent illumination.

The innovation of using a computer display in the proposed experimental setup is an important feature of this method, because it enables us to control the characteristics of the displayed patterns in real time. In particular, we take benefit of this feature by (1) numerically displacing the fringes to use phase-shifting methods and obtain more accurate results, (2) changing the fringe period (or grating pitch) to adjust the sensibility of the measurement in function of the phase variation of the object to test, and (3) varying the fringe orientation angle to obtain the desired wavefront slope components. All these changes are made without using moving mechanical parts.

Experimental measurements of two ophthalmic lenses with different focal length spatial distribution have proved the versatility of this method for optical testing. It was also proved that by displaying sinusoidal fringe patterns it is possible to use standard fringe pattern processing techniques to extract the phase information. Additionally, as all of the setup is fully programmable, this method provides an easy approach to develop, test, and compare the performance of different fringe-processing algorithms. In this way, the algorithm testing can be performed under ''real'' measurement conditions, taking into account that these conditions (the fringe profile, period, orientation, modulation, noise, etc.) can be controlled precisely (and repetitively) because no mechanicals adjustments must be made in the setup. In the future, enhancing the displaying and fringe-processing methods, it could be possible to have a real-time wavefront measurement device for use in industrial optical testing.

Acknowledgments

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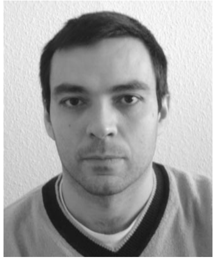

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