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Progressive power lens measurement by low coherence speckle interferometry

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A B S T R A C T

This work proposes a method for dioptric power mapping of progressive lenses through dual wavelength, low-coherence digital speckle pattern interferometry. Lens characterization finds several applications and is extremely useful in the fields of ophthalmology and astronomy, among others. The optical setup employs two red diode lasers which are conveniently aligned and tuned in order to generate a synthetic wavelength. The resulting speckle image formed onto a diffusive glass plate positioned behind the test lens appears covered of contour interference fringes describing the deformation on the light wavefront due to the analyzed lens. By employing phase stepping and phase unwrapping methods the wavefront phase was retrieved and then expressed in terms of a Zernike series. From this series, expressions for the dioptric power and astigmatic power were derived as a function of the x- and y-coordinates of the lens aperture. One spherical and two progressive lenses were measured. The experimental results presented a good agreement with those obtained through a commercial lensometer, showing the potentialities of the method.

1. Introduction

Progressive power lenses (PPL) are among the most widely used solutions for presbyopia and other disorders associated to the loss of crystalline elasticity. Recent progress in free-form technologies has been enabled a great improvement of the quality of such ophthalmic components. If compared with discrete-like bifocal lenses, the most distinguishing property of PPL is a non-constant radius of curvature of one of its surfaces, resulting in a continuous dioptric power distribution. The power increases toward the lens bottom region, such that the upper part of the lens is suitable for distant vision and the lower part, for near vision. In addition, PPL have a region connecting the upper and lower regions which allows an intermediate range between near and distant vision. As a consequence of its geometry the progressive lenses present a progression corridor — also called as umbilical region [1] — with spherical power and null astigmatism which are narrower in the region of intermediate vision and wider in the regions of distant and near vision.

In literature several methods for lens measurement based either on ray optics or wave optics have been reported [2–9]. However, most of those techniques were capable of characterizing single-power spherical lenses only. The measurement of aspherical lenses or spatially dependent power distribution lenses requires a larger number of factors to be taken into account, resulting in more sophisticated techniques.

Progressive lenses were traditionally measured by conventional lensometers (also known as focimeters), through which the dioptric power — or its reciprocal, the focal length — is determined point-by-point, making the lens evaluation lengthy, cumbersome, and limited to spherical power measurement only. With the increasing acceptance of progressive lenses and the great improvement of manufacturing techniques a special attention has been given to the analysis of such lenses, with the introduction of whole-field techniques. In this scenario the most successfull method for PPL characterization is based in the Shack–Hartmann (SH) aberrometer [10–14], which has resulted in the development of commercial devices. Other techniques, such as moiré deflectometry [15], crossed-cylinder aberroscopy [16], ray tracing [17], modified SH scanning laser aberrometry [18], etc. have been used principally for research purposes.

Whole-field interferometry is a powerful tool for lens characterization [19]. Among the interferometric methods, digital speckle pattern interferometry (DSPI) is a very well-established technique whose typical setups are comprised by very simple and low-cost optical components. It has shown to be a very suitable technique for whole-field lens analysis, since the spatial resolution of TV cameras used for image acquisition far exceeds the typical resolution of the SH aberrometer, which is limited by the distance between the microlenses of its lens array.

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In this framework the present article proposes a technique for PPL characterization through dual-wavelength DSPI. Two detuned diode lasers illuminate the optical setup resulting in a synthetic wavelength, such that the speckle pattern describing the wavefront generated by the lens appeared modulated by contour fringes. After fringe pattern evaluation the wavefront was reconstructed and its height coordinate was written as a function of a Zernike series. Those series are formed by an infinite number of complete sets of polynomials usually written as a function of polar coordinates ρ and θ. Zernike series are widely used in ophthalmology and ophthalmologic instruments for aberration evaluation of the eye or for wavefront data representation in astronomical telescopes [20–23]. From the obtained height coordinate we derived expressions to evaluate the spherical and the cylindrical power distribution of the lens and compared the results with the ones obtained through a commercial PPL lensometer for three lenses.

2. Two-wavelength whole-field digital speckle interferometry

Consider the interference of the reference and object waves with amplitudes R_0 and S_0, respectively, originated from lasers 1 and 2 at a CCD sensor. The emission of the lasers are centered at λ_1 and λ_2, such that $|\lambda_1-\lambda_2|\ll(\lambda_1\lambda_2)^{1/2}$. In order to match the spatial frequency of the interference pattern to the pixels size of the CCD sensor, both interfering beams are nearly collinear. Thus, the resulting light intensity at the CCD has the appearance of a high-spatial frequency speckle pattern with a strong background due to the plane reference wave, which significantly lowers the speckle pattern visibility. This visibility can be enhanced by means of the subtractive method [24,25], as follows: the first speckle pattern is acquired and stored, and a sinusoidal jitter signal is applied to a piezoelectrical transducer supporting one of the mirrors of the setup in order to decorrelate the speckle pattern. The pattern in this second configuration is also acquired and stored. Both frames are then subtracted and low-pass filtered using FFT (Fast Fourier Transform). Due to the heterodyne speckle interferometry process, the resulting image intensity $I(x,y)$ of the object shows a background-free object covered by low-spatial frequency contour fringes according to [25]:

$$I(x,y)=I_0\cos^2\left[\frac{\pi}{\lambda_S}(\Gamma_S(x,y)-\Gamma_R)\right] \tag{1}$$

where I_0 is the bias intensity of the speckle pattern, $\Gamma_S(x,y)$ is the optical paths of the object wave through point (x,y) on the object surface, Γ_R is the optical path of the object wave, and $\lambda_S\equiv\lambda_1\lambda_2/|\lambda_2-\lambda_1|$ is the synthetic wavelength. Notice that the equation above was obtained considering that only the waves originated from the same laser are mutually coherent [26]. Since the reference wave is planar, the phase $(\Gamma_S(x,y)-\Gamma_R)\pi/\lambda_S$ describes the object shape. The contour (bright or dark) fringes thus correspond to the intersection of the object surface with parallel, equally spaced planes of constant elevation. The distance Δz between two adjacent planes, known as contour interval, depends on the object illumination scheme. In our setup configuration using a phase object, one gets $\Delta z=\lambda_S$. The illumination setup also has a strong influence on the direction of the elevation planes, and it is of crucial importance for a correct reconstruction of the object wavefront [27].

Fringe pattern evaluation can be carried out through several phase-shifting techniques [28,29]. In the current work the phase was obtained through the four-stepping method, which consists in acquiring and combining four sequentially $\pi/2$-phase shifted interferograms with respect to the synthetic wavelength with intensities I_0, I_1, I_2, and I_3,. In this case, the surface phase δ_S is given by

$$\delta_S(x,y)=\frac{1}{2}\arctan\left(\frac{I_1-I_3}{I_0-I_2}\right) \tag{2}$$

Since the phase above is defined in the range between $-\pi$ and π only, the wavefront is reconstructed by unwrapping the phase through the branch-cut method [30].

3. Calculation of the spatial power distribution

Consider the transmission of a plane wave through a lens. By calculating the curvature of the wavefront emerging from the lens its back focal length — or, correspondingly, its dioptric power — can

be determined. Ideally perfect, aberration-free spherical lenses generate spherical wavefronts with an unique radius of curvature R, which corresponds to an unique power $1/R$. However, power-distributed lenses generate rather complex wavefronts with different local curvatures, each one corresponding to a local power.

The coordinates H of a point on the wavefront can be written as a Zernike series. Those series form a complete set of polynomials which are orthogonal inside a circle of unitary radius. They are usually expressed in terms of polar coordinates ρ and θ but can also be written as a function of the cartesian coordinates and weighted by the Zernike coefficients $A_{n,m}$ according to [21,31]:

$$H(\rho,\theta)=\sum_{n,m}A_{n,m}Z_{n,m}(\rho,\theta) \tag{3}$$

The Zernike polynomial $Z_{n,m}(\rho,\theta)$ is defined as

$$Z_{n,m}(\rho,\theta)=\begin{cases}\sqrt{2(n+1)}R_n^m(\rho)\cos(m\theta) & \text{for} \quad m\geq 0\\ -\sqrt{2(n+1)}R_n^m(\rho)\sin(m\theta) & \text{for} \quad m<0\end{cases} \tag{4a, 4b}$$

The radial function $R_n^m(\rho,\theta)$ in turn is written as

$$R_n^m(\rho,\theta)=\sum_{s=0}^{(n-|m|)/2}\frac{(-1)^s(n-s)!}{s![(n+|m|)/2-s]![(n+|m|)/2-s]!}\rho^{n-2s} \tag{5}$$

In the formulae above the n value denotes the radial dependence and is a positive integer or zero. The m value represents the azimuthal degree and relates to n according to $m=-n,-n+2,\ldots,n-2,n$. The set of coefficients $A_{n,m}$ can be obtained from the orthogonality properties of the Zernike polynomials as

$$A_{n,m}=\int_0^1\int_{-0}^{2\pi}Z_{n,m}(\rho,\theta)H(\rho,\theta)\rho d\theta d\rho \tag{6}$$

Since the (cylinder) astigmatism along the x-direction is an important parameter of a progressive lens, it is convenient to express the wavefront coordinate H in terms of the cartesian coordinates $x=\rho\sin\theta$ and $y=\rho\cos\theta$.

Once the Zernike polynomials of a given reconstructed wavefront are obtained, it is possible to calculate the spatial power distribution. Consider a wavefront emerging from the test lens expressed in terms of a Zernike series $H(x,y)$ and two light rays p and q propagating through two neighboring points $P(x_p,y_p)$ and $Q(x_Q,y_Q)$ on the wavefront. Both rays are parallel to $\hat{n}_P$ and $\hat{n}_Q$ vectors, which in turn are normal to the reconstructed wavefront. The plane located to distance f from the wavefront where p and q rays converge is the focal plane of the lens, so that the local optical power is written as $\phi_{PL}(x,y)=1/f(x,y)$, where point (x,y) lays at the vicinity of P and Q.

Fig. 1 shows $H(x)$ on plane $y=y_p$. The vector $\vec{p}_x$ is tangent to this curve at $x=x_p$, and is given by $\vec{p}_x=\vec{i}+m_{x_P}\vec{k}$, where $m_{x_P}=\partial H(x)/\partial x|_{x=x_P}$. Analogously, the tangent vector to the curve $H(y)$ on plane $x=x_p$ at the coordinate $y=y_p$ is $\vec{p}_y=\vec{j}+m_{y_P}\vec{k}$, where $m_{y_P}=\partial H(y)/\partial y|_{y=y_P}$. The normal vector $\hat{n}_P$ to the