A method is presented for measuring the modulation transfer function of ophthalmic lenses by use of the generation of laser speckle with an integrating sphere. The measurements are performed with a rectangular double-slit aperture positioned at the output port of the integrating sphere. The distance between the lens and the detector determines the spatial frequency being tested; therefore high frequencies are tested close to the lens and low frequencies are tested far away from the lens. We can conclude that the double-slit method can be a versatile technique for comparing the optical quality of ophthalmic lenses from different makers.

Optical characterization of ophthalmic lenses by means of modulation transfer function determination from a laser speckle pattern

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1. Introduction

The determination of the modulation transfer function (MTF) enables us to evaluate the image quality of a system and to characterize the spatial-frequency response of an imaging system. For measuring this function, the literature offers different methods that differ essentially in the type of target used as the object. One of the methods is based on the use of random patterns. These patterns can be generated in many ways: for example, on a computer screen or by use of random transparency targets or laser speckle patterns.

The present work presents a method for measuring the MTF of ophthalmic lenses by the generation of laser speckle with an integrating sphere. The laser radiation at the output port of the sphere passes through a double-slit aperture, which determines the spatial-frequency content of the speckle pattern that falls on the charge-coupled device (CCD). The MTF is measured for lenses of two different manufacturers (M1 and M2), and the results are compared.

In this work, we do not attempt to simulate the conditions of vision. When the lens is combined with the eye, the optical performance of the complete system can be investigated by a separate analysis of the lens and the eye. In terms of the MTF, one can determine the MTF of the complete system (MTFtotal) in a simple way by multiplying the MTF of each subsystem by using

$$\text{MTF}_{\text{total}} = \text{MTF}_{\text{CCD}} \times \text{MTF}_{\text{lens}} \times \text{MTF}_{\text{eye}}. \quad (1)$$

The influence of visual parameters such as pupil size, distance of vision, or ocular aberrations can be taken into account in the MTFeye term. In addition, the factor MTFeye can be determined by other procedures—for example, from physiological eye models or with the Hartmann–Shack sensor.

The flexibility and potential of the method that we propose comes from the fact that we can analyze the MTF of each subsystem separately. This enables us to have control over the influence of each subsystem in the degradation of the final image. In addition, we can quantify the degree to which the subsystem degrades the final image.

The method proposed here thus constitutes a relatively simple and versatile technique and could be used to measure the MTF of contact lenses, although with the added difficulty of its small diameter.

2. Experimental Device

The experimental device (Fig. 1) comprises a He–Ne laser source ($\lambda = 632.8 \text{ nm}; 17 \text{ mW}$), an integrating sphere ($\phi = 152.4 \text{ mm}$), an optical bench on which a...
linear polarizer is situated together with a double-slit aperture, the lens, which is the object of the study, and the CCD camera, connected to its control card installed in a personal computer. The laser radiation is aimed at the input aperture of the integrating sphere, generating the speckle pattern at the output aperture. These conditions ensure that the power spectral density (PSD) of the speckle irradiance in the CCD is proportional to the autocorrelation of the pupil function plus a delta function of zero frequency.\textsuperscript{10,11} The relationship between the PSDs is given by

$$\text{PSD}_{\text{output}}(\xi, \eta) = [\text{MTF}(\xi, \eta)]^2 \text{PSD}_{\text{input}}(\xi, \eta),$$  \hspace{1cm} (2)$$

where $\xi$ and $\eta$ are the spatial frequencies corresponding to the horizontal and the vertical directions $x$ and $y$, respectively. When the theoretical $\text{PSD}_{\text{input}}$ is known for the double slit and the $\text{PSD}_{\text{output}}$ is measured by the CCD, it is possible to determine the MTF of the device by Eq. (2).

The measurements are performed with a rectangular double-slit aperture positioned at the output port of the integrating sphere. Given the geometry of this aperture, the $\text{PSD}_{\text{input}}$ can be separated into the frequencies $\xi$ and $\eta$. In this work, we consider the $\text{PSD}_{\text{input}}(\xi)$ and therefore have determined the horizontal MTF. Each of the rectangular apertures of the double-slit aperture used is $l_1 = 0.70$ mm wide and $l_2 = 10$ mm tall, with a separation between centers of $L = 7.3$ mm.\textsuperscript{12}

When we consider the ensemble in Fig. 1, taking into account that the aperture is a double slit, the PSD is given by

$$\text{PSD}_{\text{input}}(\xi, \eta)$$

$$= \langle |I|^2 \rangle^2 = \frac{1}{2} \left[ \frac{\delta(\xi, \eta)}{\xi^2} \right] \left[ \frac{\delta(\xi, \eta)}{\eta^2} \right]$$

$$+ \frac{1}{4} \left[ \frac{\delta(\xi - L/\lambda, \eta)}{\xi^2} \right] \left[ \frac{\delta(\xi + L/\lambda, \eta)}{\eta^2} \right] + \frac{1}{4} \left[ \frac{\delta(\xi, \eta - L/\lambda)}{\xi^2} \right] \left[ \frac{\delta(\xi, \eta + L/\lambda)}{\eta^2} \right],$$  \hspace{1cm} (3)$$

where $\delta(X) = 1 - |X|$ for $|X| \leq 1$ and zero elsewhere, $\langle |I|^2 \rangle$ is the square of the average speckle irradiance, and $z$ is the distance between the observation plane and the exit pupil of the system. In this way, the double-slit aperture determines the content in spatial frequency of the speckle pattern registered on the CCD.\textsuperscript{13}

For the measurements, a high-resolution CCD monochrome PixelFly array was used, which comprised a matrix of $1360 \times 1024$ pixels (horizontal $\times$ vertical) as well as horizontal and vertical spacing between pixels $\Delta x$ of 4.65 $\mu$m. The Nyquist spatial frequency for a CCD with a spacing between pixels $\Delta x$ is given by $f_{\text{Ny}} = 1/(2\Delta x)$, providing a Nyquist frequency of 107.5 cycles/mm in both directions.

For the imaging processing, the appropriate software was developed with version 6.1 of MATLAB.

3. Data Processing

For the optical characterization of each of the lenses, the CCD was situated at 50 different positions with respect to the lens and, at each of these positions, ten frames were taken and averaged to reduce the temporal noise.\textsuperscript{14} From the resulting frame, the dark frame was subtracted, and a region of $600 \times 600$ pixels pixels was selected. A fast Fourier transform was performed on each row of the speckle data. The magnitude squared in one dimension provided a single estimate of the one-dimensional power spectrum, $\text{PSD}_{\text{output}}(\xi)$. These 600 spectra were averaged together for a better signal-to-noise ratio in the PSD.\textsuperscript{14} The frames were stored in tiff format without compression, at an integration time of 0.7 s. This process was followed for each position of the CCD.

The double-slit aperture provides a peak at the PSD centered on a frequency that depends on the distance between the CCD and the lens. Thus the distance between the lens and the detector determines the spatial frequency being tested, and therefore high frequencies are tested close to the lens and low frequencies are tested far away from the lens. It suffices to measure the maximum value of this peak, after normalizing the PSD to the unit for frequency zero and taking the square root to establish the value of the MTF at the frequency that is being evaluated at that moment.

Figure 2 shows a section of speckle pattern captured with the CCD and an example of normalized PSD determined with a lens of +3D from manufacturer M1.

If the $L$ lens were not used in Fig. 1, the distance $z$ in Eq. (3) would be the distance between the double-slit aperture and the CCD. When a lens is placed between the double-slit aperture and the CCD, $z$ is the distance between the exit pupil of the system and the CCD.\textsuperscript{10} It is worth noting that it is not necessary to know $z$ because the frequency that is being evalu-
ated at each point is revealed on performing the Fourier transform of the speckle pattern, as shown in Fig. 2(b).

4. Results and Discussion

Figure 3 presents the MTF of the total system (lens + CCD) for the lenses of manufacturer M2. The experimental data were fit to a second-order polynomial, with correlation coefficients of 0.89, 0.81, 0.88, 0.93, and 0.91 for the 0D (zero-power lens), −5D, −3D, +3D, and +5D lenses, respectively.

The figure shows that the lenses with negative powers present higher MTF values than do the lenses with positive power. On the other hand, in the case of the negative lenses, the lens of −5D gave higher values than did the lens of −3D. For the positive lenses, the lens of +5D resulted in lower values than for the lens of +3D.

Figures 4 and 5 show a comparison of the lenses of +3D and −3D for the two manufacturers. With the lenses of manufacturer M1, higher values were found than for those of manufacturer M2, indicating greater optical quality with respect to the MTF. The fit of the experimental data to second-order polynomials for the −3D and +3D lenses of manufacturer M1 was 0.92 and 0.90, respectively. We have represented the error bars corresponding to the standard deviation for manufacturer M1, calculated from 20 measurements for each position of the CCD. It bears noting that the error bars are greater for the low spatial frequencies. This is due to the weaker signal’s reaching the CCD, because, as stated in Section 3, the low frequencies are tested far away from the lens and therefore from the laser source. The standard deviation decreases as the spatial frequency increases. In the case of the +3D lens (Fig. 4), from the frequency of 79.8 cycles/mm, the standard deviation is consistently less than the subtraction of the MTF values between the two manufacturers. Thus, for example, for 79.8 cycles/mm, the standard deviation is 0.015, and the subtraction of the values of the MTF between

Fig. 3. (Color online) MTF of the total system for the lenses of manufacturer M2.

Fig. 4. MTF found with lens of +3D for the two manufacturers. The error bars represent the standard deviation in the case of the lens of manufacturer M1.
the two manufacturers is 0.02. For 181.7 cycles/mm, the subtraction between the MTFs of manufacturers M1 and M2 is 0.04 and the standard deviation is 0.005. In the case of the 3D lens (Fig. 5), from the frequency of 42.6 cycles/mm, the standard deviation is invariably lower than the subtraction of the values between the two manufacturers. For 42.6 cycles/mm, the subtraction of the MTF values between the two manufacturers is 0.02 and the standard deviation is 0.015. For 107.7 cycles/mm, the subtraction between the MTFs is 0.03 and the standard deviation is 0.010.

Figure 6 shows, on the ordinate axis, the quotient of the MTF curves for the lenses of 3D and 3D of manufacturers M1 and M2. This type of representation offers an important advantage; that is, on making the quotient between the two curves, we succeed in canceling the modulation effect in spatial frequency that the CCD itself introduces. For the 3D lens, the MTF of the lens of manufacturer M1 is consistently higher than that of manufacturer M2. For the −3D lens, the MTF in the case of manufacturer M1 is greater than that of manufacturer M2, but, as opposed to the lens of +3D, it begins later to diminish from the Nyquist frequency (107.5 cycles/mm) onwards.

An important advantage of the double-slit method is that the greatest spatial frequency that can be measured is approximately twice the Nyquist frequency of the CCD. The main disadvantage of this method is the necessity of moving the CCD in order to measure within a broad range of spatial frequencies. This disadvantage can be avoided if a single aperture is used, but in this case the MTF measurements are limited to spatial frequencies somewhat below the Nyquist frequency. However, with a single aperture, it would be possible to determine the MTF of the lens in one measurement.

5. Conclusions
In this work, we have performed an optical characterization of ophthalmic lenses by the laser speckle pattern generated with an integrating sphere. The MTF was determined for lenses of positive and negative powers. Also, the results were compared with those of lenses made by two different manufacturers.

With these results, we conclude that the double-slit method offers a versatile technique for comparing the optical quality of ophthalmic lenses from different makers.

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References

