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Abstract. Some experimental qualitative results are presented with a setup that uses a knife edge for producing partial interferograms, in order to obtain the quality of a lens under test. However, the same method can be extended to test an optical surface. The knife edge is located near the focal point of the lens, covering almost half of the incident laser light beam. The different observed interferograms correspond to the orientation of the knife edge with respect to the optical axis, and its distance to the focus of the lens. [DOI: 10.1117/1.OE.53.9.092006]

Keywords: interferometry; testing of lens; optical aberrations.

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1 Introduction

Following the work done by Cornejo et al.,[1] who produced an interference pattern with the edge of a knife to find out the wavelength of a laser used as source of light later on, emerged the idea to apply such a technique for testing a lens or an optical convergent system. One advantage of using only a knife edge is that a reference wavefront is produced that is superimposed on the wavefront under test coming from a lens (Fig. 1). On the other hand, using the knife edge, no auxiliary optics is required, and in addition this kind of interferometer is a common path one. Therefore, the environment does not affect the experimental setup and the interference pattern is nonlocalized. As will be shown in the next sections, a disadvantage is that partial interferograms are observed, but different interferograms can be produced depending on the orientation of the knife edge, and fast qualitative analysis can be realized,[2–4] to find out the quality of the lens or optical system tested. In this paper, for the first time, quantitative results are given for testing a certified lens from Zygo Co (Middlefield, Connecticut). An abstract[2] and previous papers by Korneev et al.[3,4] explained how some problems were solved for the knife edge interferometer, such as the alignment of the setup, to improve the contrast of the interferogram fringes, and the stitching of the partial interferograms into a complete one.

2 Mathematical Analysis

In Fig. 1, a scheme of the experimental setup is shown; in Fig. 2, the experimental distances L_1, L_0, and L_2 are described, as they are used to find the locations of the fringes in the interferograms. The knife edge can be located before or after the focal point of the lens under test. In Fig. 2, we describe the situation where the knife edge is located before the focal point. For rays starting at points A and A', and reaching point C, on a plane where the interferogram is observed, the optical path difference (OPD) is equal to

$$\mathrm{OPD} = (\overline{A'B} + \overline{BC}) - \overline{AC}, \tag{1}$$

since points A' and A are at the same distance from point B, because the wavefront is spherical, then Eq. (1) can be rewritten as

$$\mathrm{OPD} = (\overline{AB} + \overline{BC}) - \overline{AC} = L_1 + \sqrt{L_0^2 + L_2^2} - \sqrt{(L_0 + L_1)^2 + L_2^2}. \tag{2}$$

From the theory of the phenomena of interference,[5] the phase for dark fringes in an interferogram is given by $\delta\varphi = (2n+1)\pi$, where n is the order of the interference of the fringe. Therefore, the (OPD) can be expressed as

$$(\mathrm{OPD}) = \left(n + \frac{1}{2}\right)\lambda. \tag{3}$$

However, since the wavefront touching the knife edge produces a cylindrical reference wavefront, according to the diffraction theory, a correction must be done to Eq. (3),[6] then

$$(\mathrm{OPD}) = \left(n + \frac{5}{8}\right)\lambda. \tag{4}$$

A comparison between theory and experiment was carried out after the following steps: the experimental positions of the dark fringes in the interferograms of Fig. 3, with their intensity profiles of Fig. 4, are written in Table 1 as L_2E. The corresponding values calculated with Eqs. (3) and (4) are listed as L_2T and L_2T, respectively. Small differences can be noticed between the values for the theoretical values.

3 Experimental Arrangement

As a first step, to use the described interferometer to obtain quantitative results, a high-quality lens was tested. To ensure the quality of the lens, a reference certified lens from Zygo Co. was selected. Such lens was fixed at the exit of a Zygo interferometer. As a matter of fact, this Zygo instrument is

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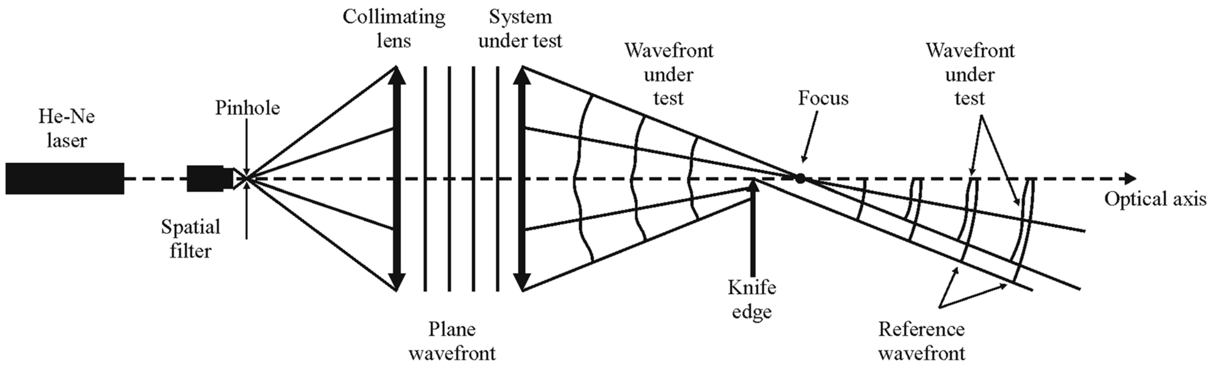


Fig. 1 Interferometer operation principle.

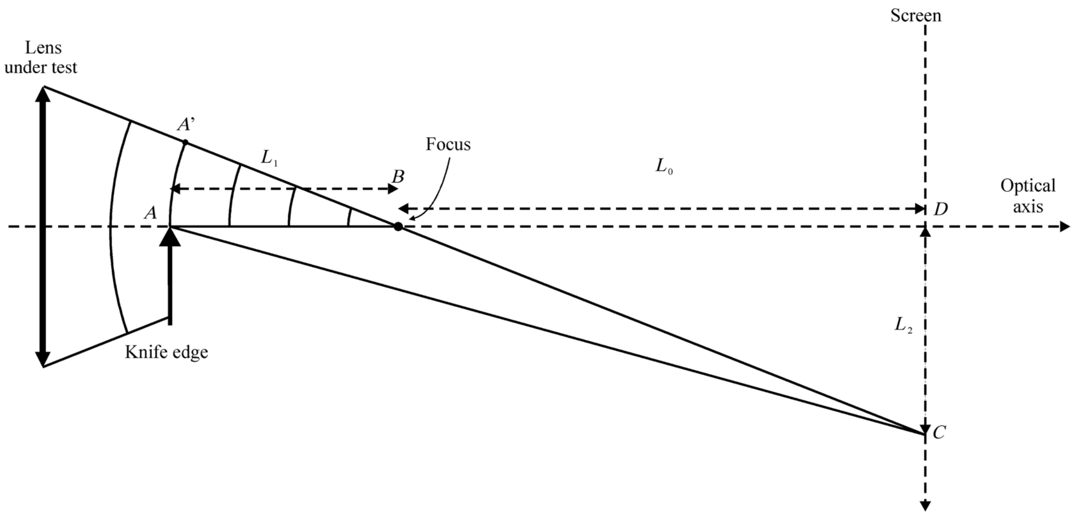


Fig. 2 The blade is placed between the lens under test and focus.

a Fizeau interferometer.[7,8] In this case, the lens under test is illuminated by collimated He-Ne laser beam coming from the Zygo interferometer.

The experimental setup is shown in Fig. 5. The knife edge is located before the focal point of the lens, and the knife edge is fixed on a mechanical stage with three perpendicular movements.

This specific mounting of the knife edge was necessary because its location must be known precisely with respect to the focal point of the lens under test and must be perpendicular to its optical axis. If the knife edge is not positioned accurately, low-quality interferograms are observed. The position of the knife edge and the screen of Fig. 5 correspond to the distances L_1 and L_0 from Fig. 2, respectively. Since, it is very important to have a precise alignment of all the experimental setup for the measurements of the distances L_0 and L_1 with respect to the focal point. The following

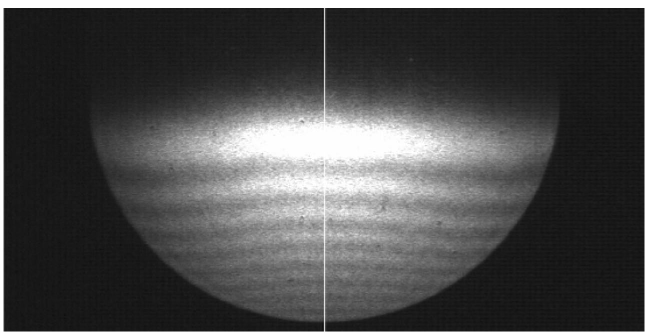


Fig. 3 Interference patterns for eight dark fringes, $L_1 = 0.5$ mm.

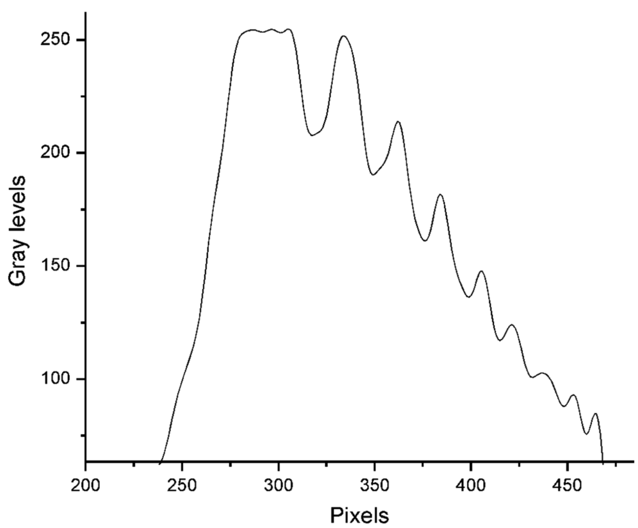


Fig. 4 Intensity profiles of the scanned meridional line for the interference patterns of Fig. 6, eight fringes.

Table 1 Experimental and theoretical values for positions of the interference fringes for eight fringes.

n	L_2E (mm)	L_2T [Eq. (3)]	L_2T [Eq. (4)]
1	38.062	40.257	41.906
2	51.547	52.021	53.312
3	63.727	61.611	62.709
4	73.297	69.927	70.900
5	80.692	77.381	78.265
6	88.087	84.203	85.019
7	95.047	90.535	91.297
8	100.268	96.475	97.193

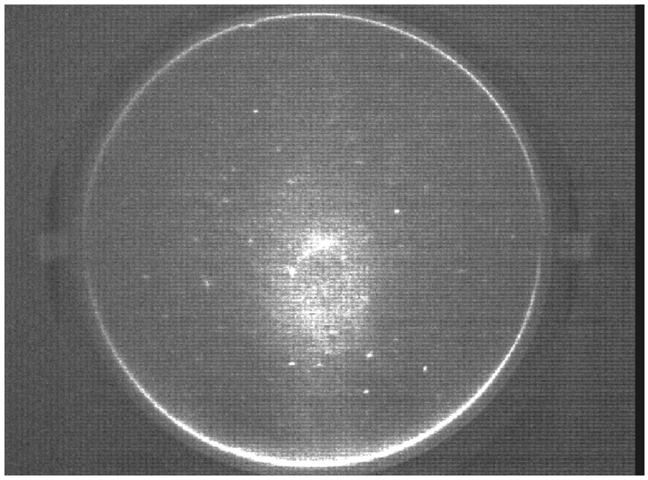


Fig. 6 The knife edge is placed at the focus lens.

procedure was used: (i) the knife edge is located just at the focal point and for that position, interference pattern is not observed; (ii) therefore, for that position, the knife edge is rotated for four perpendicular directions around the optical axis, and the uniform illumination must be observed on the screen, as it is shown in Fig. 6.

Once a proper alignment of the interferometer and the lens under test are reached, the knife edge can be located to some distance, L_1, from the focal point. The interferogram shown in Fig. 7 is for the distance of $L_1 = 0.35$ mm, and four orientations of the knife positions: below (0 deg), right (90 deg), above (180 deg), and left (270 deg) with $L_0 = 652.1 \pm 0.1$ mm. The number of fringes in the interferograms can be changed if the distance L_1 of the knife edge from the focal point is shifted to different positions (see Figs. 8–10).

4 Experimental Results and Interferograms Analysis

In this section, for the first time, quantitative experimental results will be described, using the knife edge interferometer proposed in this paper. The lens under test is a certified lens from Zygo Co, already mentioned, with a focal length of 338.08 mm, a diameter of 10.16 mm, and $f/3.3$. The certified quality is $\lambda/20$. The experimental arrangement has the distance $L_0 = 652.1 \pm 0.1$ mm, the light source is a He-Ne laser with $\lambda = 632.8$ nm, with the power of 12 mw, and three different distances L_1.

Since, with this knife edge interferometer, partial interferograms are observed, as shown in Fig. 7. In order to have complete interferograms, a stitching of the vertical [Figs. 7(a) and 7(c)] and horizontal [Figs. 7(b) and 7(d)] interferograms was done. The interferograms of Figs. 8–10 are given as results. The adjustment of the half interferograms was done after the following steps: (a) first checking the focus position for each experiment, as explained in Sec. 3 and (b) using the outer rings of two interferograms along the same directions, vertical and horizontal. Those rings are well defined and can be seen clearly in the interferogram images because of the careful alignment reached in the experiment.

The stitched interferograms for three different values of L_1 equal to 0.35, 0.40, and 0.50 mm, respectively, are shown in Figs. 8–10. Because the different values of the

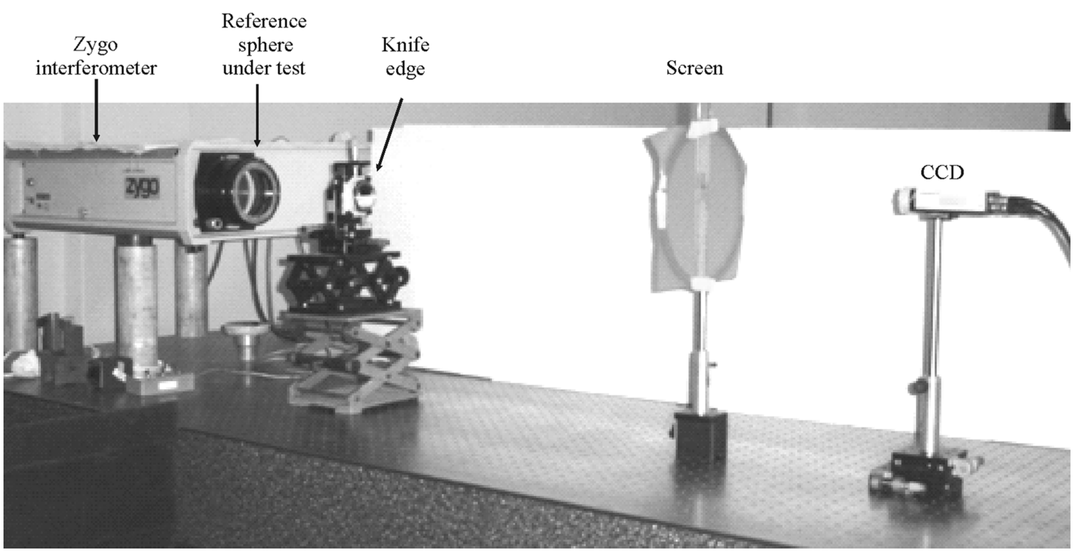
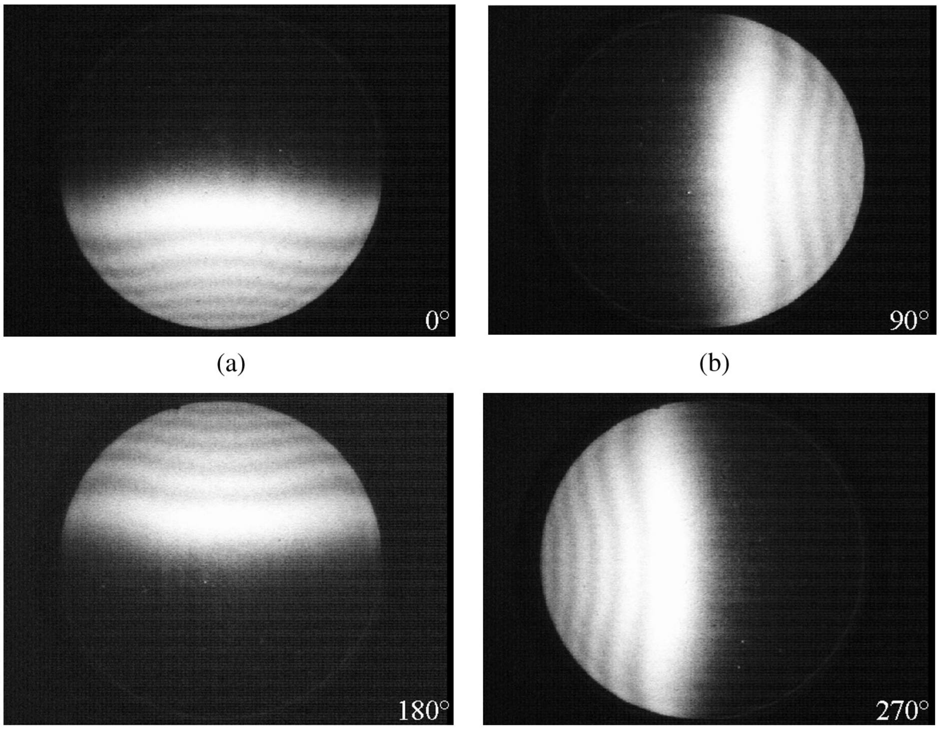
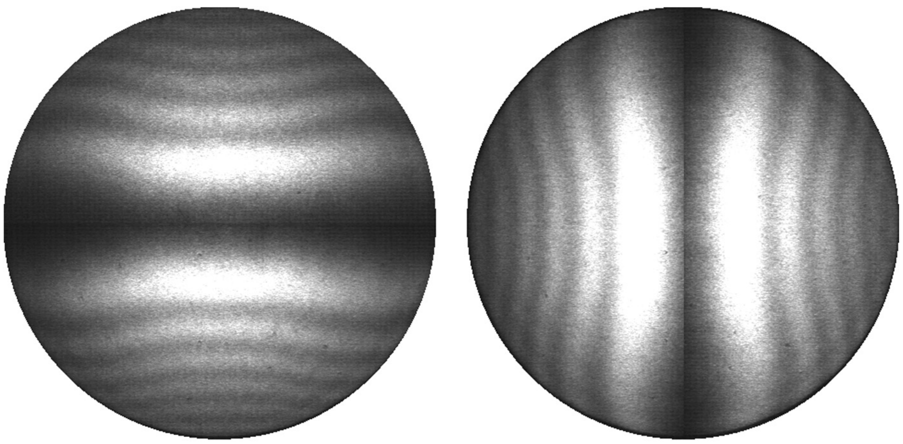


Fig. 5 Experimental setup for testing a reference sphere.



(a) (b) (c) (d)

Fig. 7 Interference pattern for $L_1 = 0.35$ mm.



(a) (b)

Fig. 8 Interference half patterns overlapped for five fringes dark, for $L_1 = 0.35$ mm knife edge position.

distance L_1, those interferograms of Figs. 8–10 have different numbers of interference fringes. The idea to have such interferograms, with different number of fringes, is that when they are analyzed, the final results obtained have consistent numerical values. Therefore, the knife edge interferometer is a robust instrument and can be used for the optical testing of lenses.

Given that we are interested to obtain quantitative results, the commercial program APEX® (Interferogram Analysis Software; Lambda Research Corporation, Littleton, Massachusetts) was used to analyze the complete interferograms.

As results of using the program APEX, the aberration coefficients are given in Tables 2–4,[8,9] and the root mean square (RMS) and peak-to-valley values corresponding to each one of the interferograms are shown in Figs. 8–10. An important aspect that we would like to mention using the APEX software is the fact that the interference patterns must have good contrast, in order to know precisely the fringe positions. The wavefront fitting method applied by APEX is the least square fitting with the Gram–Schmidt orthogonalization.[10]

Tables 2–4 are split into two columns, labeled according to the kind of interferograms analyzed, either in the horizontal or vertical directions. For the piston, focus, and tilt coefficients, the values reported within the same table are equal with small difference; however, when Tables 2–4 are compared, such parameters are different for each case, as can be

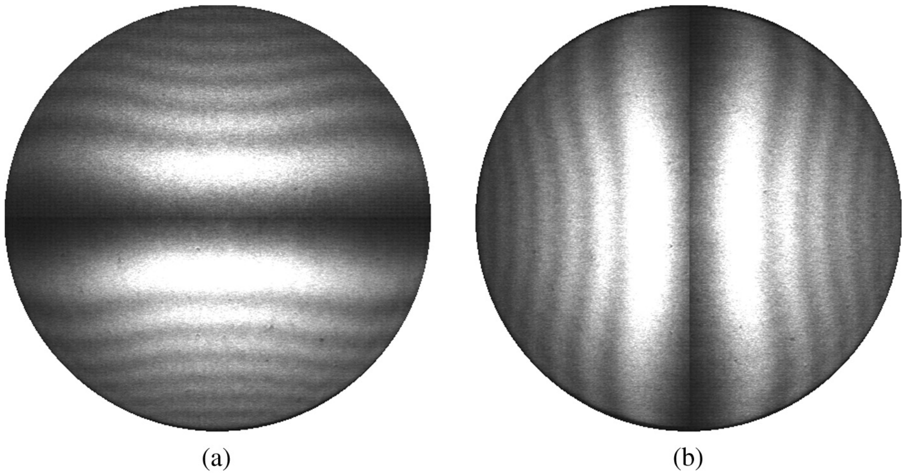


Fig. 9 Interference half patterns overlapped for six fringes dark, for $L_1 = 0.40$ mm knife edge position.

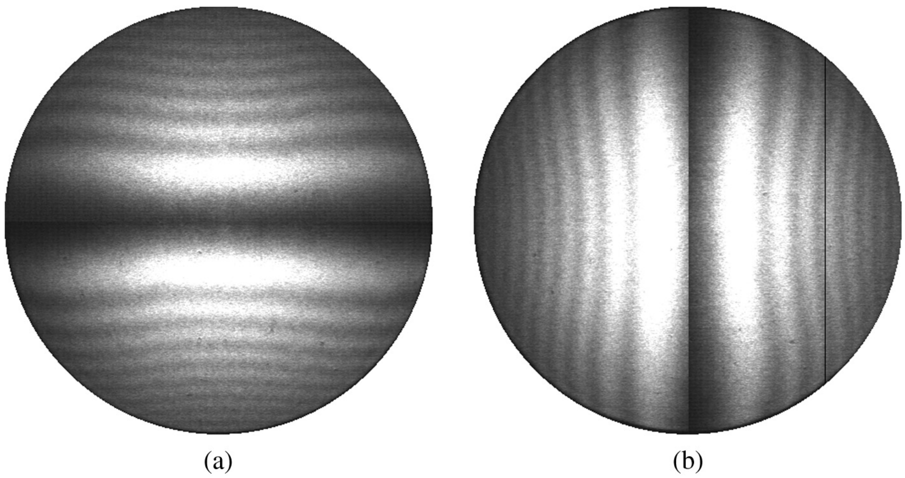


Fig. 10 Interference half patterns overlapped for eight fringes dark, for $L_1 = 0.5$ mm knife edge position.

Table 2 Aberration coefficients derived with the commercial program APEX, for half overlapped interferograms, five fringes; for vertical and horizontal interferograms.

Aberration coefficients	Interferograms horizontal (≅)	Interferograms vertical (≅)
Piston	0.645	0.72
Focus	0.575	0.585
Tilt *Y*	0	0.055
Tilt *X*	0.02	−0.14
Spherical	0.02	−0.005
Coma *Y*	0.035	−0.025
Coma *X*	0	0.05
Astigmatism 45 deg	−0.01	−0.025
Astigmatism 0 deg	−1.625	1.615
RMS	0.06	0.05
Peak-to-valley	2.51	2.25

Table 3 Aberration coefficients derived with the commercial program APEX, for half overlapped interferograms, six fringes; for vertical and horizontal interferograms.

Aberration coefficients	Interferograms horizontal (≅)	Interferograms vertical (≅)
Piston	0.78	0.815
Focus	0.73	0.7
Tilt *Y*	−0.055	0.035
Tilt *X*	0.02	−0.155
Spherical	0.005	−0.02
Coma *Y*	0.035	−0.005
Coma *X*	−0.015	0.045
Astigmatism 45 deg	0.01	−0.01
Astigmatism 0 deg	−1.885	1.83
RMS	0.06	0.05
Peak-to-valley	2.59	2.74

Table 4 Aberration coefficients derived with the commercial program APEX, for half overlapped interferograms, eight fringes; for vertical and horizontal interferograms.

Aberration coefficients	Interferograms horizontal (≅)	Interferograms vertical (≅)
Piston	0.985	1.09
Focus	0.95	0.955
Tilt Y	−0.065	0.035
Tilt X	0.015	−0.415
Spherical	0.02	−0.04
Coma Y	0.03	0
Coma X	−0.01	0.05
Astigmatism 45 deg	0.015	−0.02
Astigmatism 0 deg	−2.335	2.285
RMS	0.06	0.06
Peak-to-valley	3.6	3.55

expected, because its values depend on the number of fringes and the knife edge position. With respect to the spherical, coma, and astigmatism aberration coefficients for each table (Tables 2–4), the aberration values are different until the second digit; however, when Tables 2–4 are compared, the numerical values are different again until the second digit, except for the astigmatism 0 deg. Therefore, our quantitative experimental results are consistent, even with interferograms with different numbers of fringes and either in the vertical and horizontal directions. By comparison with the certified value of the Zygo lens equal to $\lambda/20$, the RMS value derived for all the interferograms from our experiment is equal to 0.06 from the three tables that is equivalent to $\lambda/20$.

5 Conclusions and Comments

The proposal of the knife edge interferometer presented in this paper seems to work properly for deriving quantitative results for the testing of lenses. In the case of the Zygo lens tested, the quality had been confirmed using either vertical or horizontal interferograms and even with different numbers of interference fringes. However, in order to consider a spherical reference wavefront, a maximum shift of the knife edge is for producing eight interference fringes. The numerical values derived for different aberration coefficients had shown consistency in all cases; this result had been achieved because of the procedures explained for a proper alignment of the interferometer. Hence, a careful alignment is compulsory, as it is required in all interferometric methods. The stitching of two half interferograms used seems to be a good technique.

For future work, different stitching techniques[11] will be applied, with the knife edge located above and below the optical axis; at the present time, some tests are carried out eliminating the collimated lens in our setup and testing directly the lens just illuminated by a point light source on axis, either coherent or incoherent.

As comments, the two aspects to be considered about the method described here, given its relevance and pointed out by the reviewers, are the following. (a) In the case where the lens under test is not very well corrected, the image, at the focal point on the knife edge, will produce a complex wavefront that in turn will produce distorted interferograms. However, in general, in the field of optical testing of optical systems under test, using interferometry, the quality of the systems must have a high degree of correction, producing focal points with high quality, in order to avoid the analysis of complex interferograms. (b) As explained in the text, there is a limitation on the number of fringes that can be analyzed in the interferograms, as a method to have a spherical wavefront incident in the knife edge. This last requirement is not compulsory if the surface or system under test produces cylindrical wavefronts.

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