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## The sensitivity of the common focus error of a reference lens on the measurement accuracy in a Fizeau interferometer

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**Abstract.** A technique used to examine the performance of reference lens of interferometer is described. The defects in the reference lens that are primarily due to the manufacturing errors or the assembly errors or both will result in the common focus error of reference lens at the centre of curvature of reference surface, which affects the measurement accuracy. The optical path difference between the reference wave front and the test wave front at the exit pupil is applied to analyse the influence of common focus error of reference lens on the measurement errors. A comparison of the experimental result with the numerical analysis is made.

### 1. Introduction

The Fizeau interferometer is widely used to examine a fine surface, but the influence of imperfect common focus of reference lens is rarely discussed. A common Fizeau interferometer is shown in figure 1. The laser beam through a micro-objective and a pinhole, as a spatial filter, forms a point source and then propagates through a beam splitter, a collimating lens and a reference lens to produce a convergent or divergent wave front. The last surface of the reference lens is referred to as the reference surface of the interferometer. The reference lens is usually designed in such a way that the ray is normally incident upon the reference surface. In other words, the transmitted rays which emerge from the reference lens are focused at the centre of curvature of the reference surface. The test surface is set so that its centre of curvature coincides with that of the reference surface. The two surfaces construct the confocal cavity. The two reflected beams (one from the reference surface and the other from the test surface) propagate back through the reference lens and the collimating lens and are then reflected by the beam splitter to an aperture stop. Viewing optics are then used to form the interference fringes on the detector.

There have been many papers on the measurement accuracy of interferometer technology published in the past [1–6]. Selberg [1, 2] discussed several different optical errors present in interferometer system and the effect of the errors on measurement accuracy. He analysed four sources of errors including optical cavity

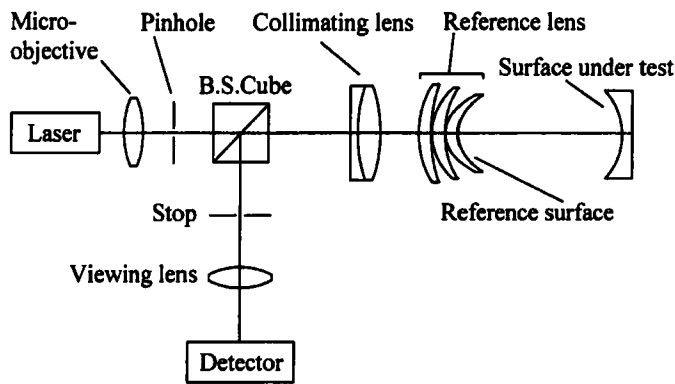


Figure 1. Common Fizeau interferometer.

errors, imaging distortion, ray-mapping errors and detector noise. Optical cavity errors are typically the primary limitation on measurement accuracy. Some papers concentrated on the aberrational analysis of the interferometric system [3–6]. Mehta [3] considered the refraction errors for interferometric measurements in multicomponent systems. Jozwicki [4, 5] studied the influence of aberrations of interferometer elements on measurement errors, using wave aberration theory. The aberrations of the optical system which consists of the interferometer cavity and the viewing optics can result in fringe distortion. Huang [6] discussed the propagation error from the pupil shearing of the viewing system. However, what is less understood is the influence of the imperfections of reference lens on measurement accuracy. Because of the manufacturing errors or the assembly errors of reference lens or both, the transmitted rays are not normal to the reference surface, the requirement of common focus of reference lens is destroyed, and the measurement accuracy is thus influenced.

In this paper, we present a simple method to analyse the performance of the reference lens with a common focus error. We discuss the influence of the common focus error of reference lens on measurement accuracy, which helps us to understand how good a reference lens is required for an interferometer. A reference lens with  $F/3.3$  was manufactured to verify the analysis.

## 2. Theory

### 2.1. Description of examination of the reference lens

Figure 2 schematically illustrates the arrangement of a Fizeau optical system in which a standard reference plane is used to examine the performance of the reference lens under test. The reference wave is reflected from the uncoated standard reference plane which is indicated in figure 2. After passing through the standard reference plane, the test wave propagates through the whole reference lens under test and is partially reflected from the last uncoated surface back to the interferometer by the same paths. Most of the defects in the reference lens under test will make the incident, transmitted and reflected rays not normal to the last surface and result in a common focus error at the centre of curvature of the reference surface. The information on the common focus error of the reference

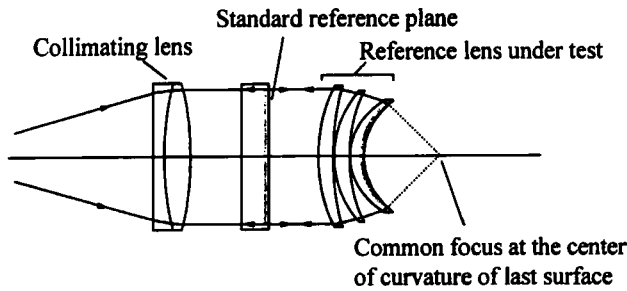


Figure 2. A Fizeau interferometer for examining the performance of the reference lens by use of a standard reference plane.

lens under test is carried by the reflected test wave and so can be evaluated from the interference fringes. All the manufacturing errors including the curvature, thickness and index of optical elements and the assembly errors of reference lens can make the interference pattern shown in deformed fringes. The number of interference rings in the fringe pattern shows the quantity of the common focus error and indicates the performance of the reference lens.

## 2.2. Evaluation of measurement errors of interferometer

To evaluate the measurement errors of interferometer arising from the common focus error of reference lens, we put the reference lens with common focus error into the interferometer shown in figure 1 to measure the figure of the test surface. In this analysis, we use a perfect spherical surface as the test surface to avoid the measurement errors from the test surface. Using ray tracing, we calculate the optical path difference (OPD) between the reference and test wave fronts at the exit pupil as shown in figure 3, which will be expressed as

$$\begin{aligned} OPD &= W_{\text{ref}} - W_{\text{test}} \\ &= (W_{\text{r,opd}} - W_{\text{t,opd}}) + (W_{\text{r,perf}} - W_{\text{t,perf}}), \end{aligned} \quad (1)$$

where  $W_{\text{r,opd}}$  and  $W_{\text{t,opd}}$  are the OPDs of the reference wave front and the test wave front relative to their perfect spheres, respectively.  $W_{\text{r,perf}}$  and  $W_{\text{t,perf}}$  are the perfect spheres of the reference and test wave fronts, respectively. Zernike [7] polynomials are used to fit the OPDs of measured data points in the interfering wave front owing to their orthogonality property [8, 9]. Using a least-squares fit, we represent the interfering wave front as a linear combination of Zernike polynomials. The aberrations from, for example, piston, tilt and defocus should be removed in the fitted Zernike polynomials since these terms are introduced by the measurement process. The piston term represents an offset at the  $z$  axis, the tilt term is caused by the slanted test surface and the defocus term describes a shift in focus from the diffraction focus. After removal of these terms, the OPDs of measured data points are then recalculated and the peak-to-valley (PV) and rms measurement errors are obtained.

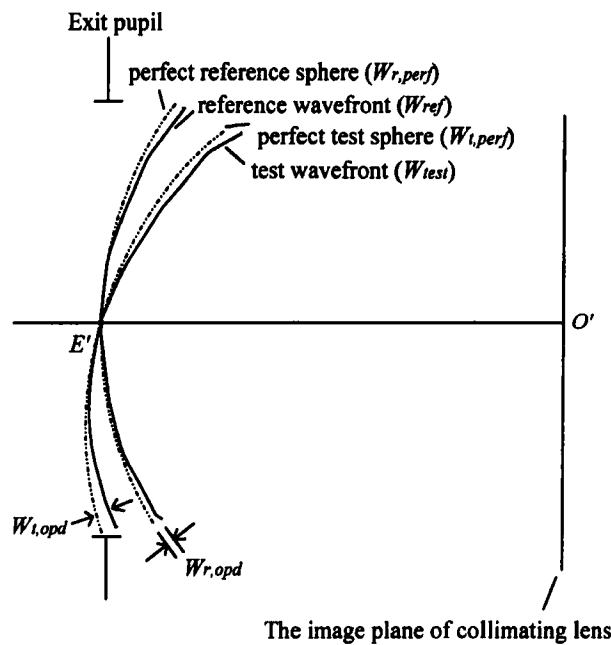


Figure 3. The reference and test wave fronts at the exit pupil.

### 3. Numerical calculation

We designed a Fizeau interferometer and an  $F/3.3$  reference lens to analyse the influence of common focus error of reference lens on measurement errors. Using the method for examination mentioned in section 2.1, we generated one to seven interference rings by introducing different common focus errors of the  $F/3.3$  reference lens. These interference rings are the interfering result of the standard reference plane wave and the test wave from the  $F/3.3$  reference lens under test. As described in section 2.2, we measured a concave surface with a radius of 50 mm, using the  $F/3.3$  reference lens with common focus error. The test surface was slightly tilted to obtain sufficient interference line fringes for measurement. Here we produced six line fringes. The OPD of interference fringes, given by equation (1), was calculated by ray tracing. The measurement errors were then obtained. The table shows the measurement errors resulting from the different common focus errors of the  $F/3.3$  reference lens. In this example, we find that the PV measurement errors are less than 0.01 wave even if the common focus error reaches seven interference rings. The simulation results show that the sensitivity of common focus error of reference lens is not serious. Of course, the quantitative analysis of measurement error depends on the reference lens design.

### 4. Experiment

In order to verify this analysis, the Zygo Fizeau interferometer was used to examine the reference lens by the method shown in figure 2. A reference flat with the surface figure of  $\lambda/50$  PV was used as the standard reference plane to examine the  $F/3.3$  reference lens whose optical parameters were used in the numerical

Measurement errors resulting from the different common focus errors of the  $F/3.3$  reference lens. The common focus errors are represented by the number of interference rings.

Common focus error (ring)	PV error ( $\lambda$ )	RMS error ( $\lambda$ )
1	0.003 512	0.000 741
2	0.004 061	0.000 808
3	0.004 609	0.001 004
4	0.005 181	0.001 174
5	0.005 724	0.001 351
6	0.006 265	0.001 533
7	0.006 803	0.001 718

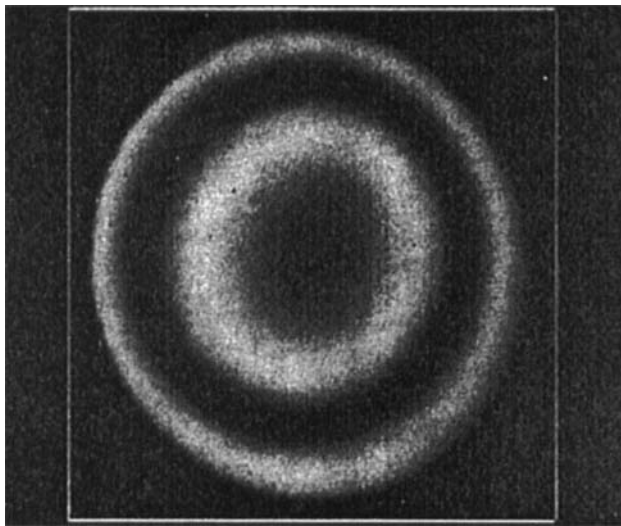


Figure 4. Interference rings of the  $F/3.3$  reference lens. The common focus errors are represented by the number of interference rings.

analysis. The interference rings are shown in figure 4. Referring to the table, we find that the  $F/3.3$  reference lens with common focus error of within three interference rings will be good enough to use for investigating commercial-grade elements, systems or surfaces that typically have values greater than  $\lambda/10$  PV; of course, the flatness of reference surface has to be required to a certain grade. We also have numerically analysed other reference lenses with different  $F$  numbers and have similar results of the same order of magnitude as in the table. Although except for reference lens the aberrations of the other optical elements in the interferometer could make the rays not parallel before entering reference lens and produce the common focus error of reference lens, those errors have been evaluated in advance and are negligible in both numerical calculation and experiment, compared with the errors arising from the defects in the reference lens.

## 5. Conclusion

We have presented a simple technique and related formulae to examine the tolerance of common focus of reference lens in the Fizeau interferometer. The result shows that the sensitivity of common focus error is not serious as we expected. This analysis will help the lens designer to understand the effect of the performance of reference lens on measurement accuracy.

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