Double Focus Interferometers and the Influence of Their Sample Setting Errors

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Double focus interferometers are attractive for reducing the influence of ambient conditions due to their common-path configuration. This paper describes the influence of sample setting errors in these interferometers. They have been divided into two types, i.e. the normal illumination type and the oblique illumination type. For each type, an equation of the measurement error due to sample setting error has been derived with Gaussian optics. The measurement error of the normal illumination type becomes a parabolic function of the position on the sample surface. The derived error equations have been verified by ray tracing and by experiment. The error of the oblique type is smaller than that of the normal type.

Key words: double focus interferometer, error analysis, sample setting error

1. Introduction

Some double focus interferometers had been proposed for testing spherical mirrors, lenses and surface profiling.1–5 Their optical systems use double focus elements such as a scatter plate, a zone plate, a birefringent lens, and cyclic design optics. Double focus interferometers are attractive for reducing the influence of ambient conditions due to their common-path configuration. Especially, since the reference beams are converged and reflected at a point on the surface under test, the effect of mechanical vibration is very small. In recent research, the double focus interferometers have adopted the phase shift technique to make more precise measurements.6–9

The measurement results with double focus interferometers involve measurement errors. The errors are caused by imperfection of optical elements, alignment error of the optical system, and setting errors of the samples. The error due to the optical elements and the alignment error is systematic, and so can be calibrated. On the other hand, that due to sample setting error is not systematic. To obtain an ideal reference, the sample surface has to be put at the convergence point of the reference beams. However, it is difficult to set the sample surface with no setting error.

Double focus interferometers have not been discussed previously from the viewpoint of sample setting errors. In this paper, we discuss the influence of sample setting error and present a way of making the measurement error clear. To avoid discussions on each double focus interferometer one by one, the interferometers have been classified into two types and the influence has been discussed on each type in turn. In Sec. 3, the measurement error equations of the sample setting error will be derived using Gaussian optics. The equations have been verified by numerical calculations of the ray tracing and compared with experimental results.

2. Optical Systems

Double focus interferometers may be classified in terms of double focus elements such as the scatter plate, the zone plate etc. However, to discuss the influence of the sample setting error, we should pay attention to the structure of their optical systems. From the viewpoint of the test beams illuminating the sample surfaces, double focus interferometers are classified into two types; one is the “normal illumination type” whose test beams illuminate the test surface normally, and the other one is the “oblique illumination type” whose test beams illuminate at varying angles to the normal direction of the test surface.

Figure 1(a) shows a schematic diagram of a surface profiling optical system for the normal illumination type. The double focus element DFE works as a zero power lens and a positive power lens. In this example, the light beams collimated by DFE are the reference beams. They are converged by the objective OL and illuminate a reference point on the surface. The light beams uncollimated by DFE are the test beams. They illuminate the surface under test normally. The test beams reflected from the test surface pass through DFE again without refraction, and make an image of the test surface on the image sensor by imaging lens IL. The test and reference beams reflected from the surface under test interfere with each other after passing the DFE.

When the surface under test is flat and is placed at the ideal reference plane, the test beam illuminates the surface normally and the reference beam illuminates the reference point with angle γ. This incident angle γ depends on the illuminating point of the sample surface. The test beam illuminating the boundary of the measurement area interferes with the reference beam with the maximum incident angle; the test beam illuminating the center interferes with the reference beam illuminating the same point normally, and its incident angle γ is zero.

Figure 1(b) is a schematic diagram of the oblique illumination type. The DFE also works as a zero and positive
power lens in this type. In this case, the light beams passing through DFE without refraction become the reference beams. However, when the reference beams pass through DFE again after reflection from the sample surface, the beams are refracted by DFE. The test beams directed toward the sample are refracted by DFE and the beams passing DFE again after reflection are not refracted. The incident angle of the test beam is not constant, and is dependent on the illuminating point on the sample surface. The test beam with incident angle \( \gamma \) ideally interferes with the reference beam of the same angle.

3. Aberration Equations

Figure 2 shows the geometry of light beams of the normal illumination type. Focal lengths of DFE, OL and IL are \( f_i, f_z \) and \( f_s \), respectively. The reference point on the sample surface is placed with deviation \( Z_0 \) from the ideal reference plane and has a slope of angle \( \beta \). The measurement point has deviation \( Z_a \) with slope angle \( \alpha \). The difference between \( Z_a \) and \( Z_0 \) is the surface profile to be measured. The reference beam reflected from \( K \) interferes with the test beam from \( k \) on the observation plane \( R \).

The measurement error is the change in the optical path difference at the observation point \( R \) due to the sample setting error. Since all optical elements are assumed to have no aberrations and \( P \) is the conjugate point of \( R \), we may calculate the optical path difference between the test and reference beams to the conjugate point \( P \). For the test beam, the deviation of the optical path is \([b-c-k]\), and for the reference beam, the deviation is \([K-C-L]\) with the approximation of \([P-D-L] \approx [P-D'-K]\). The measurement error \( \Delta L_a \) becomes

\[
\Delta L_a = [b-c-k] - [K-C-L] = Z_a \left( 1 - \frac{1}{\cos 2\alpha} \right) - Z_0 \left( 1 + \frac{1}{\cos \theta} \right) .
\]

(1)

In this equation, \( \gamma \) is the ideal incident angle and \( \theta \) is the actual angle of the interference beam reaching a point \( R \).

If Eq. (1) is expanded in a Taylor series and the terms higher than third order are neglected, the optical path difference is approximated by the following equation,

\[
\Delta L_a = 2(Z_a - Z_0) + 2Z_a\alpha^2 - 2Z_0\beta^2 + Z_0\gamma^2 .
\]

(2)

The first term on the right-hand side corresponds to twice the size of the surface profile to be measured, and the remaining terms correspond to the measurement error we are discussing. The second term \( 2Z_a\alpha^2 \) appears in the error for ordinary interferometers with a separate reference plane.

Figure 3 shows the geometry of light beams of the oblique illumination type. \( Z_0, Z_3, \alpha \) and \( \beta \) are the setting errors and the slope angles of the measurement and reference points, respectively. The incident angles of the reference and test beams are the same and denoted by \( \gamma \). \( \theta \) and \( \xi \) are their actual incident angles. \( P \) is the conjugate point of \( R \) for the reference beam and \( c \) is that of \( R \) for the test beam. The deviation of the optical path of the test beam is \([k-c-l]\) with the approximation \([Q-b-l] \approx [Q-b'\cdot k]\), and that of the reference beam is \([K-C-L]\) with \([P-D-L] \approx [P-D'\cdot K]\). Then the optical path difference \( \Delta L_a \) is expressed by

\[
\Delta L_a = [k-c-l] - [K-C-L] = \frac{Z_0}{\cos \xi} \left( 1 + \cos (\xi - \gamma) \right) - \frac{Z_0}{\cos \theta} \left( 1 + \cos (\theta - \gamma) \right) .
\]

(3)

If Eq. (3) is expanded in a Taylor series and the terms higher than third order are neglected,

\[
\Delta L_a = 2(Z_a - Z_0) + 2Z_a\alpha^2 - 2Z_0\beta^2 + (Z_a - Z_0)\gamma^2 .
\]

(4)
The first term on the right-hand side corresponds to the surface profile, and the remaining terms are the measurement error. Only the last term differs from Eq. (2).

When the surface under test is very smooth but not optically flat, angles $\alpha$ and $\beta$ are much smaller than $\gamma$ and $\theta$. In this case, the last term $Z_\alpha \gamma^4$ dominates the aberration for the normal incident type, and $(Z_\alpha - Z_\beta) \gamma^2$ dominates for the oblique incident type. If the test surface is an exactly flat plane, the measurement error of the oblique illumination type is reduced because $Z_\alpha - Z_\beta$ is very small in comparison with $Z_\alpha$. For the normal illumination type, the error is proportional to the setting error $Z_\alpha$ and the square of angle $\gamma$. Angle $\gamma$ depends on the measurement point, and measurement with the normal illumination type contains the parabolic aberration.

4. Ray Tracing and Experimental Results

This section shows the results of ray tracing for a double focus interferometer using a birefringent lens and corresponding experimental results.

We adopted the ray tracing program made for interferometers with a birefringent double focus lens which is a symmetric triplet of LaK7/calcite/LaK7. The focal lengths of the birefringent lens were 38.5 mm for extraordinary rays and 555 mm for ordinary rays. The lens diameter was 2.3 mm. The focal lengths of the objectives of the both interferometers were 180 mm. The maximum incident angles of the interferometers were $0.37^\circ$.

It has been assumed that optical parts have no aberration with exception of the birefringent lens. Ray tracing was made in a case where the surface under test was a flat plane and it was displaced towards the objective as the setting error. The calculated measurement profile was composed of the differences in wave fronts of the test and reference beams. The errors were evaluated by the difference in calculated profiles before and after the sample movements, since the systematic error due to the double focus lens is not the present interest. The calculated errors are shown as solid circles in Fig. 4. The horizontal axis shows the distance from the center of the measurement area, i.e. the distance between C and c in Figs. 2 and 3. The solid lines are the results from Eqs. (2) and (4). The sample setting errors, i.e. the distances of the movements, were 1 mm, 2 mm and 3 mm. The results of the oblique illumination types have no measurement error for all displacements of the sample plane, as shown as a horizontal line in Fig. 4. These ray tracing results are in good agreement with the results of the equations.

The experiments were performed for the two types of interferometers with birefringent lenses whose focal lengths were the same as that of the ray tracing. The
optical systems were basically the same as those of the ray tracing with the exception that the objective and imaging lenses were single lenses which may have aberrations. The measurement systems adopted the polarization phase shift technique to obtain high sensitivities. In the experiments, we measured a surface profile of an aluminum-coated mirror.

Figure 5 shows a result of the normal illumination type. The line in Fig. 5(a) is the difference of the measured profiles with the surface displacement of 3 mm. To retrieve the error due to displacement, the tilt of the sample plate was compensated and the profile data were spatially averaged during the calculation procedure. Figure 5(b) is the corresponding difference calculated with Eq. (2). Although the experimental result involved a few nanometers of noise, the result is in good agreement with that obtained from the equation.

Figure 6 shows the result with 3 mm movement for the oblique incident type. The experimental result had a noise level of 10 nm. This result did not show a large parabolic curvature such as that in Fig. 5(a), and the measurement result agreed with that from the equation.

5. Discussion
In the above section, the error equations have been verified by ray tracing and experiments. When the sample surface is completely flat, the normal illumination type has a larger measurement error than the oblique type for the same setting error. However, when the deviation $Z_{G}-Z_{E}$ of the surface profile from the ideal flat surface is a few micrometers and we can make the setting error $Z_{E}$ smaller than 10 μm, the last terms of Eqs. (2) and (4) become of the same order. As an example of 10 μm setting error and 2 μm deviation, the measurement errors become 8 nm with an incident angle $\gamma$ of 5° for the normal illumination type, and 2 nm for the oblique illumination type.

6. Conclusion
We have discussed the influences of the sample setting errors of the double focus interferometers. The interferometers were classified into the two types, and the error equation was derived for each type. To verify the equations, we made calculations of the ray tracing and experiments. These results satisfied the derived equations.

References