Orthogonal ray scheme: a method for processing interference patterns and reconstructing the shape of a test convex mirror

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Abstract. This report is devoted to the processing of the interference pattern of the tested mirror, obtained using the orthogonal ray scheme, where the convex testing surface is illuminated by a collimated beam, which is perpendicular to the optical axis of the surface. The interference pattern is created by two wavefronts, one of which is reflected from the mirror, while the other wavefront bypasses the mirror and travels directly to the detector plane. The result of interference pattern processing is a topography map formed by several tangential profiles. The proposed method is suited for large diameter convex spherical and aspherical mirrors and does not require a priori information of surface under the test, such as the vertex radius of curvature and the conical constant. Theoretical foundation of the data processing method are presented.

1. Introduction
The development of testing methods for convex aspherical and spherical mirrors of large diameter is an urgent task. To reduce figure errors during the manufacturing phase, one needs to have reliable testing techniques, which in the case of large convex mirrors requires bulky optical setups based on Hindle sphere or other compensatory reflective optics [8]. Thus, when testing convex aspherical and spherical optical surfaces by traditional methods, it is necessary to use precision optical elements with a diameter larger than the diameter of the test surface [5-7]. This problem is especially urgent due to the new generation of very large grand-based optical telescopes [1-5] in which a convex secondary mirror is used to reduce the length of the optical system of the telescope [1, 6-9].

At present, an interference method for testing convex aspherical mirrors based on the orthogonal ray scheme is being developed [10-13], which does not require the use of large-diameter auxiliary optical elements [6-8]. The report is devoted to the processing of the interference pattern obtained by the proposed interference method.

2. Theoretical foundation of the data processing method
The basis of the proposed interference method is in the illumination scheme with a collimated beam directed orthogonally to the optical axis [5-9]. The interference pattern is created by two wavefronts,
one of which is reflected from the mirror (object beam), while the other wavefront (reference beam) bypasses the mirror and travels directly to the detector plane, see figure 1. The detector plane is located at a distance $s$ from the vertex of tested surface. The measurement result is the coordinates of the interference fringes.

The interference pattern is a system of fringes. Fringe width depends upon optical path difference between the object and reference beams and decreases from the vertex of the tested mirror to the edge of it.

The distribution of the optical path difference of the interference pattern is known depending on the coordinate in the detector plane $\Delta (h)$. The optical path difference can be determined as (figure 1)

$$\Delta B = PB - AB. \quad (1)$$

The coordinates of the point $P$ are unknown, and the task of reconstructing the tested profile is define it. Point $P$ belongs to a curve for which the following geometrical relations is true

$$PB - AB = \text{const} = \Delta B. \quad (2)$$

The locus of points $P$ satisfying (2) is a parabola with a geometric focus coinciding with point $B$ (figure 2). By the same reasoning, each tested surface point lies on the corresponding parabola.

To find the equation of the profile under test we need write the equation of the parabola using a Cartesian coordinate system $YOZ$ with its origin at the vertex of the mirror under the test. First, we introduce an auxiliary $YO'Z'$ coordinate system with the origin at the vertex of the parabola (figure 2). The canonical equation for a parabola of the local coordinate system $YO'Z'$ is

$$y' = \frac{z'^2}{2p(h)}, \quad (3)$$

where parameter $p$ is the distance from the focus of the parabola to the directrix.

The distribution of the distance $p$ depends from coordinate $h$ reflected object beam. The distance $p$ depends on the coordinate $h$ of the object beam (1) in the detector plane.

In order to find the canonical equation for a parabola of the $YOZ$ coordinate system, we express equation (3) in the local $YO'Z'$ coordinate system through the global $YOZ$ coordinate system

$$y(z) = \left(\frac{-z-h}{2p(h)}\right) - \left(s + \frac{p(h)}{2}\right), \quad (4)$$

where $h$ is the height of the reflected ray in the detector plane, which depends on the $z$ coordinate of the reflection of ray (1) from the surface under the test (figure 1).
Figure 2. To the definition of the parabola equation.

Since the segments $PB$ and $PK$ are equal by the definition of a parabola, the path difference $PB - AB = \Delta$ is also equal to $AL - AB = p$. Therefore, the parabola parameter $p$ is equal to the difference between the paths of the beams $PB$ and $ABp = \Delta$.

Figure 3. The test mirror is the envelope of the parabola family.

As a result of measurements in practice, two data sets are obtained: $h$ and $\Delta$, which can be approximated by the function $h(\Delta)$. The parametric equation of the $i$-th parabola in the XOY coordinate system

$$y_i(z) = \left(\frac{-z-h_i(\Delta_i)}{2\Delta_i}\right) - \left(s + \frac{\Delta_i}{2}\right),$$  \hspace{1cm} (5)$$

where $\Delta_i$ is a parameter that is an element of the array $\Delta$.  

To determine the coordinates of the set of points $P$ belonging to the tested surface, it is necessary to find the envelope of the family of parabolas.

To find the coordinates of an arbitrary point $P_i$, you need to solve the system of equations

\[
\begin{align*}
F_i(y, z, \Delta) &= 0 \\
\frac{dF_i(y, z, \Delta)}{d\Delta} &= 0. 
\end{align*}
\]  

(6)

Thus, reconstructing the profile of the tested surface (figure 3) is reduced to solving systems of equations (6). The result of measurement is a topography map formed by several tangential profiles.

3. Conclusion

The method for reconstructing of topography convex aspherical and spherical mirrors with various geometrical parameters has been developed. The present method may be applied for convex surfaces without the a priori information of it, such as the vertex radius of curvature and the conical constant.

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