Orthogonal ray interferometer: modification for testing convex and concave mirror surfaces

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Abstract. A non-contact optical method for testing of large concave and convex mirrors both spherical and aspheric is presented. It is based on the orthogonal ray interferometer modification. The point source is placed near the testing mirror and the chief ray propagates normally to its axis. The information about a tangential profile of testing mirror is contained in an interference pattern that is a result of superposition between two wavefronts, the first is reflected from the mirror, the second bypasses the mirror. Testing of the entire surface is carried out by rotating the mirror. Interferogram decoding method and algorithm for determination of an error of the testing surface are presented. The proposed method does not require bulky additional optical components what differs it from existing methods and makes promising primary for testing large astronomical mirrors. Furthermore, the method is universal and suited for surfaces with various geometrical parameters. The scheme with some modification of the present method is applied for surfaces without axis of rotational symmetry or freeform surfaces.

1. Introduction

With development of science and technology a need to improve performance of optical systems is appearing, in particular, it relates to its resolution that requires an increase in the manufacturing accuracy of individual optical elements. It includes telescopes, the development of which is experiencing actively during the last decades, especially the telescopes with extremely large optics, which enable explorations that were previously impossible, such as the discovery of celestial bodies beyond the capabilities of existing telescopes or dust-obscured star formation [1–5].

Wave front errors greatly affect image quality. This explains the high requirements for the quality of manufacturing of optical elements and for the accuracy of their testing. Most of the designed and applicable testing methods for measuring a surface error are based on analysis the interference pattern [6–9]. For testing of aspheric mirrors, the special compensators are applied (Offner lens, plate with computer synthesized hologram, etc.) [10–11]. The methods for their calculation and manufacture are well known, however, the compensator is suitable for testing only one specific mirror and cannot be
used for testing mirrors of the other shape. In this sense, the compensation method is not universal. Besides, the problem of quality testing of the compensator also exists.

2. The scheme of orthogonal rays

Compensators or other auxiliary optical components became several times larger than the testing mirror in the case of the convex mirror testing [10]. This often leads to the need to test sub-aperture mirrors; in addition, a separate compensator has to be manufactured for each zone of the test surface [12–13]. The method of orthogonal rays is a promising solution to this problem [14–15]. It is based on illumination of the testing mirror with the collimated beam that is perpendicular to the axis of its symmetry. An analysis of the reflective wavefront gives ability to calculate a mirror error.

At present, an interferometer based on the orthogonal ray scheme is being developed at All-Russian Scientific Research Institute of Metrological Service (VNIIMS) [16–17]. It is shown on figure 1. Fizeau interferometer (1) with collimator (2) generates an ideal flat wavefront of 300 mm diameter. The interferogram is a result of a superposition of the flat reference wavefront (5) bypassing the testing mirror (3) and the reflected wavefront (4). The interference pattern is a system of variable width arcs, oriented perpendicular to the mirror axis.

Since the fringe width varies from several microns to several mm, and the whole size of the interferogram is about 200 mm, there is used a digital microscope (6) mounted on a linear translation stage to measure the dependence of the fringe width on its height above the vertex of the testing mirror. Rotating the mirror about its axis allows testing of several profiles and creation of the topographic map of the tested mirror error.

Figure 1. Orthogonal ray scheme: 1 – interferometer, 2 – collimator, 3 – testing convex mirror, 4 – object beam, 5 – reference beam, 6 – microscope mounted on a translation stage, 7 – rotary stage.
Disadvantage of this scheme is inability to test concave mirrors that significantly reduces its field of application. The present report offers the modification of the optical scheme which eliminates this disadvantage.

3. The proposed testing method

The proposed optical scheme is shown in figure 2. The interferometer consists of a point source (1) (a focused laser beam), and a testing mirror (3). The fringe pattern observed at the plane (2). We use the same interferometer components as in figure 1 except for collimator (1).

The interference pattern is a result of superposition between two wavefronts, the reference beam r bypasses the mirror and the object beam propagates in the direction t2 after the reflection from the testing mirror. The interferogram represents a set of arcs with different width. The thickness b of the individual arc is related to the angle ξ between the rays r and t2

\[ b = \frac{\lambda}{\sin \xi}, \]

where \( \lambda \) is the wavelength.

![Figure 2. The proposed optical scheme: 1 – point source of spherical waves, 2 – observation plane, 3 – testing mirror.](image)

Rotating the mirror about its optical axis is needed for creation of the topographic map of the tested mirror error as in the interferometer was described in previous section.

4. Algorithm for determination an error of the testing surface

The dependence \( b(h) \) the thickness \( b \) of the individual fringe on the height of its maximum \( h \) is determined after the registration of the interference pattern. The information about a figure error of the mirror is found by the processing of the dependence \( b(h) \). The algorithm starts with consistent composing equations of the reference ray r, reflecting ray t2 and incident ray t1.

Since the position of the point source is known, the equation of the reference ray r can be found easily. The measured angle \( \xi \) offers an opportunity to reconstruct the equation of the reflective ray t2. Further the point of intersection between the reflected ray t2 and the theoretical curves of tangential profile of the testing surface is determined and then angle \( \varphi \) of inclination of the normal restored to a point is found.

If there are the errors \( \Delta z \) the obtained value of the angle \( \varphi \) will be different from theoretical value of the angle \( \varphi_0 \) that corresponds to the ideal shape of the testing mirror.

It could be assumed for small values of the shape errors that

\[ \tan(\varphi - \varphi_0) = \tan(\Delta \varphi) = \frac{d}{dy}(\Delta z). \]
The integration of the obtained expression allows to calculate the required error of the mirror shape. Figure 3 shows the results of the numerical experiment. We have modeled a spherical mirror with a radius $R = 3000$ mm, diameter $D = 200$ mm and surface error $\Delta z_0$ as shown on figure 3(a). In figure 3(b) it is shown the deviation of the angle $\phi$. The calculated surface error $\Delta z$ is shown on figure 3(c). The figure 3 shows a good match between the modeled and the calculated surface errors. Thus, the developed algorithm allows performing surface testing with high accuracy.

![Figure 3](image_url)

Figure 3. Results of numerical modeling: (a) – modeled surface error $\Delta z_0$, (b) – deviation of angle $\Delta \phi$, (c) – calculated surface error $\Delta z$.

5. Conclusion

The method for testing of large concave and convex mirrors with various geometrical parameters has been developed. Furthermore, the present method may be applied for surfaces without the axial symmetry and freeform surfaces. It also worth mentioning that the measurements are non-contact that allows testing the large-sized mirrors which are often used in modern telescopes.

This testing method does not involve additional optical elements such as compensators that makes it more universal. Furthermore, the absence of the component requires lower cost for producing the scheme that will be fabricated for less time. The algorithm will be further developed for obtain more accurate figure errors of the produced component.
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