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Stitching algorithm for subaperture test of convex aspheres with a test plate

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ABSTRACT

Subaperture stitching interferometry combined with a test plate is attractive for testing large convex aspheres, but the stitching algorithm is challenging because the aberrations induced by misaligned test surface or test plate are coupled with the surface figure. By relating the subaperture configuration to the overlapping deviations through ray trace and coordinate transformation, the subaperture misalignment is optimally recognized and corrected to give a minimal overlapping inconsistency in an iterative way. Allowing for misaligned test plate, we decompose the induced aberrations into three parts which are corrected by the stitching algorithm, removed in the form of the Zernike polynomials and left uncorrected as residuals. Finally we present simulation results of testing a convex aspheric mirror with a computer generated hologram which shows the algorithm successfully retrieves the surface figure with the test mirror or the hologram misaligned.

1. Introduction

Convex aspheric mirrors are widely used in telescopes as the secondary mirror. With the increasing aperture of the optical system, the aperture of the secondary is approaching 1 m for space telescopes [1], and even breaking through 4 m for ground-based telescopes [2]. Interferometric testing of such large convex aspheres is challenging due to the large aperture, the large aspheric departure, and the special difficulties of testing convex reflecting surfaces.

Smith and Jones [3] summarized and compared nine metrology methods for large convex mirrors. The basic three of them are the Hindle Test, Aspheric Test Plate and Through the Back Test. Unfortunately the Hindle sphere in Hindle Test is usually several times larger than the test mirror, which makes it impractical for meter-class convex mirrors. Although variations such as the Simpson–Hindle Test [3] and the Perforated Subaperture Hindle Sphere Test [1] were proposed to deal with this problem, they are strictly limited to conic aspheres and sometimes still suffer the problem of optical layout (e.g., the long path).

In Through the Back Test configuration, the convex surface is treated as a concave one by testing through the back. It is a clever choice since problems are readily solved for concave surfaces. However, it also means that the transmitted material with high transmission quality is required, and lightweight structure on the mirror substrate is not allowed. This is evidently bad for space telescopes.

Burge and Anderson [4] proposed the Aspheric Test Plate method by using either an aspheric surface or a spherical surface with computer generated hologram (CGH), which is the reference surface in a Fizeau interferometric test configuration. Although slightly larger illumination optics and test plate are required, their tolerances are greatly loosened because the quality of surfaces before the reference has no direct contribution to the measurement error due to the common-path nature. The Test Plate method was adopted for the secondary mirrors of Gemini, MMT, VLT [1] and Gran Telescopio Canarias (GTC) [5].

The aperture is still limited, typically no larger than 1 m, for the Aspheric Test Plate method. Combination with subaperture stitching interferometry seems much more attractive. Since the full aperture can be divided into several subapertures and measured one by one, subaperture stitching interferometry effectively extends the lateral range of measurement and also enhances the lateral resolution. Combining subaperture stitching interferometry with a test plate was reported as a possible solution for testing of LSST secondary and TMT secondary [2]. It should be noted that stitching itself is not competent for large convex aspheres, because the large aspheric departure results in a large number of subapertures as in a non-null test configuration [6]. Also note that QED technologies combine the stitching with a variable optical null (VON), capable of testing middle-scale aspheres [7]. The subapertures are tested in near-null configuration with most of the aberration compensated by the VON. The high precision hardware relaxes the requirements on the stitching algorithm to a great extent.

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The major problem of subaperture stitching is to correct the different misalignment of subapertures, because different mechanical motion errors are introduced and unknown when adjusting the position and orientation of subapertures. It is quite challenging when using a test plate for aspheres since basically three components are involved, i.e., the interferometer optics, the test plate and the test surface. Aberrations may be coupled with the surface figure in the measurement if any one of them is misaligned. Furthermore the aberrations induced by misalignment such as radial shift cannot be corrected by traditional stitching algorithms which correct only the heights and do nothing to lateral shift of measuring points.

This paper aims to retrieve the full aperture surface figure from subaperture measurements obtained with the test surface or the test plate misaligned. More specifically, aberrations induced by misalignment including radial shift are separated from the surface figure, though they are identical for all subapertures and appear as taken from rotationally symmetric surface figure.

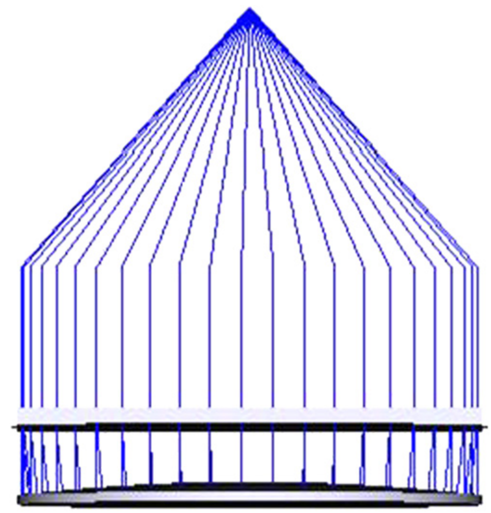

Fig. 2. Zemax model of the subaperture testing system.

2. Misalignment-induced aberrations

Careful alignment is necessary for testing aspheres with a test plate because misalignment introduces considerable aberrations which should not be counted in the surface figure. However, misalignment does exist, especially in subaperture tests since each subaperture must be positioned and oriented with regard to the test plate as in a null test configuration. Then problem arises in stitching such subaperture measurements because the misalignment-induced aberrations degrade the overlapping consistency significantly, while general stitching algorithms are based on the least-squares (LS) of overlapping deviations with proper removal of tip, tilt and power.

We begin with the following example. The test mirror is hyperbolic and convex. The clear aperture is 180 mm, the conic constant is -5.481, and the radius of curvature at the vertex is 756.489 mm. Totally six off-axis subapertures are tested with the mirror rotating around its optical axis by 60° for each. The off-axis distance is 30 mm. The test plate is a planar surface plus a CGH, illuminated by a transmission flat. Fig. 1 shows the footprint diagram of the mirror subaperture. The Zemax model of the subaperture testing system is also shown in Fig. 2.

The residual aberrations of the test system are nominally less than 0.0001λ (peak-to-valley (PV)). We now suppose that the test surface figure contains some primary aberrations. The surface sag is given by

$$z = Z_s(x^2+y^2)^2 + Z_a y^2 + Z_c y(x^2+y^2) \quad (1)$$

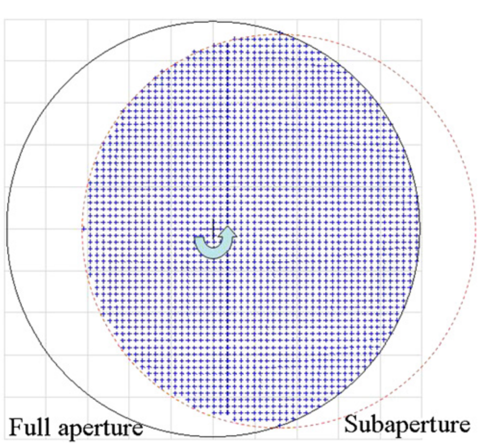

Fig. 1. Subaperture footprint diagram.

where x and y are the normalized lateral coordinates. Z_s, Z_a and Z_c are the coefficients of spherical aberration, astigmatism and coma, respectively.

Let $Z_s = 1$ μm, and $Z_a = Z_c = 0$. The surface figure is shown in Fig. 3(a) and the measured surface error of nominally aligned subaperture is half of the optical path difference (OPD), shown in Fig. 3(b). We use Zygo MetroPro to load and analyze the data obtained from Zemax in the context. When the mirror is decentered by 0.1 mm in the X direction, obviously different surface error is obtained in subaperture measurement as shown in Fig. 3(c). Note tip, tilt and power are removed in the error maps. It is evident that the subaperture misalignment introduces overlapping deviations, which cannot be minimized by simple tip–tilt-power correction as in conventional subaperture stitching algorithms. On the other hand, if we try to remove more terms from the subapertures, for example in the Zernike polynomials, by minimizing overlapping inconsistency, then the surface figure is prone to be removed along with misalignment-induced aberrations.

To overcome this problem, Burge et al. [2] suggested two additional degrees of freedom (DOFs), i.e., the radial shift and the clocking of the test plate, for stitching optimization. These two modes of misalignment are analyzed in advance by ray tracing, to get the rule of impact of them on wavefront error. The impact is represented by variation of the Zernike polynomials. Then the variation is accordingly identified and removed, along with general tip–tilt-power correction. This method is ad hoc as the impact rule should be found for different surfaces and subapertures in different test configurations. Moreover, it cannot deal with the surface figure variation except the induced aberrations due to lateral shift. It may fail to separate the induced aberrations from the surface figure when the full aperture surface figure is rotationally symmetric and the subapertures are identically misaligned, because the overlapping deviations are calculated at nominal subaperture positions while the subaperture data are sampled at misaligned positions.

For example, when the mirror is decentered by 0.1 mm and then rotated to be sampled, all subapertures are identical, as shown in Fig. 3(c). It is confusing because the misaligned subapertures look like nominally aligned ones taken from the full aperture figure of rotational symmetry. But if we put the misaligned subapertures in nominal configurations, deviations exist in the overlapping region and will not disappear until they are put in the real misaligned configurations. In Fig. 4, the two outmost subapertures are sampled at the decentered positions