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Practical retrace error correction in non-null aspheric testing: A comparison

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ABSTRACT

In non-null aspheric testing, retrace error forms the primary error source, making it hard to recognize the desired figure error from the aliasing interferograms. Careful retrace error correction is a must bearing on the testing results. Performance of three commonly employed methods in practical, i.e. the GDI (geometrical deviation based on interferometry) method, the TRW (theoretical reference wavefront) method and the ROR (reverse optimization reconstruction) method, are compared with numerical simulations and experiments. Dynamic range of these methods are sought out and the application is recommended. It is proposed that with aspherical reference wavefront, dynamic range can be further enlarged. Results show that the dynamic range of the GDI method is small while that of the TRW method can be enlarged with aspherical reference wavefront, and the ROR method achieves the largest dynamic range with highest accuracy. It is recommended that the GDI and TRW methods be applied to apertures with small figure error and small asphericity, and the ROR method for commercial and research applications calling for high accuracy and large dynamic range.

1. Introduction

Non-null aspheric testing is increasingly employed for its flexible and versatile measurement properties, especially for testing aspherics with large apertures, large departures or different parameters. By now, several non-null interferometric testing ways have been proposed, such as the SNI (sub-Nyquist interferometry) [1], the PCI (partially compensating interferometry) [2], the SSI (subaperture stitching interferometry) [3–5], the NASSI (non-null annular subaperture stitching interferometry) [6] and the TWI (Tilted Wave Interferometry) [7], etc. With non-null configurations, not only the aspheric testing range is enlarged, but also the time and costs are saved compared to the null configurations [8].

In a null test, rays impinge perpendicularly onto the test surface. However in a non-null arrangement, most rays impinge in directions that differ from the normals of the test part and travel through different paths from the origin after reflection, thus retrace error is induced [9,10]. In the final detected interferograms, fringe deformation caused by the retrace error is aliasing with that due to the aspheric figure error. Distinguishing these two major errors, that is, the retrace error correction, takes up the core algorithm in non-null aspheric test for the purpose of figure error extraction. An appropriated retrace error correction method directly impacts the accuracy of the testing results and the efficiency of the figure error reconstruction process.

Much effort has been put on this issue as listed in Table 1. Based on aberration expressions, Huang [11] derived the propagation errors due to non-common path through theoretical prediction. By empirically mapping the interferometer errors, Evans [12] proposed a correction method with aberration expansions and several measurements of a tilted off-axis flat in advance, reducing the error deviations from 150 nm to around 30 nm. It is applicable to “black box” systems but limited to low spatial frequency. With the third-order aberration theory, Murphy [13] presented a calibrating method. However, it not allows for full error characterization of the system and becomes sophisticated when imaging configuration is more than one singlet lens. For “black box” system correction, there are another two methods. One is the GDI (geometric deviation based on interferometry) method, which assumes the imaging system is perfect during the correction and is a common process in subaperture stitching tests [14]. The other is the perturbation method [15–17] that describes the interferometer with characteristic functions. Several priori measurements with the reference surface at different locations are required for system error calibration and figure error reconstruction based on the

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Table 1
Retrace error correction methods for non-null aspheric testing.

Method	Based on	Model box	Prior knowledge
Huang	Aberration expansions	Black	Relative pupil positions
Evans			Several measurements of tilted flat off-axis
Murphy		White	Parameters of the imaging system
GDI	Perfect imaging	Black	shape of the incident reference sphere
Perturbation	Perturbation theory	Black	Calibration priori done with several measurements
Separate correction	Theoretical wavefront	White	System prescription, calibrated priori to the test
TRW			
ROR	Optimized matching	White	System prescription, calibrated priori to the test
Reverse ray tracing			
Reverse optimization			System prescription, calibrated during the test

perturbation theory. Limitation of this method in practice is mechanical stability and a need of higher-order correction to improve accuracy [15]. In order to further characterize the interferometer, "white box" model is employed, in which once or multiple ray tracing of the system is utilized for retrace error correction. As shown in Table 1, based on theoretical wavefront obtained by ray tracing the interferometer model once, system inherent retrace error is corrected with separate correction method [9] or TRW (theoretical reference wavefront) method [18]. To correct retrace error induced also by the figure error of the test part, the idea of optimized matching of data from system model and experiments with multiple ray tracing and optimization of the model is first presented by team of Greivenkamp, called the reverse optimization method [10,19]. Calibration of the system model is accomplished while solving the tested figure error. Considering that multiple measurements and iterations are needed with computationally intensive and long time, it is better for system calibration. Also based on optimized matching, the ROR method (reverse optimization reconstruction) [6,20] and reverse ray tracing method [21,22] correct retrace error on a calibrated interferometer model. The latter ray traces reversely from the detector to the test surface, while the other sequentially. Retrace error is almost completely corrected in ideal simulations of both cases. It is notable that for "white box" model, system calibration is very important and has been given much attention to [10,19,23–26].

In this paper, three practical methods, i.e. the GDI, TRW and ROR methods, are analyzed and compared with successive tested figure errors and non-null wavefronts to exhibit the performance trends and dynamic ranges, instead of specifically independent testing cases as reported in previous literatures. Dynamic ranges are sought out. It is suggested to employ aspherical reference wavefronts for dynamic range enlargement, which also does much favor to the calibration of "white box" system in the meantime if the generator of the test wave is singlet lens. Experiments are presented for demonstration and application of the three methods are recommended based on the analyses.

2. Algorithms

Assume that the figure error of the tested asphere is W_{asp}. In a certain non-null system, test wavefront carrying the information of W_{asp} coherences with the reference wavefront, forming the non-null interferogram which is then imaged onto the detector. By interferograms analyzation, the wavefront detected at image plane noted as W_{det} can be extracted, which is an aliasing of the information of W_{asp} and retrace error. With retrace error corrected, W_{asp} is able to be reconstructed from W_{det}.

2.1. The GDI method

It is known in a null test, OPD between the reference wave and the test wave is twice the W_{asp} if the incident rays reflect once on the test part. Figure error is obtained as half of the detected wavefront. As for non-null test, shape difference between reference wavefront and the tested asphere is not only W_{asp}, but also the geometric deviation (W_{gdv}) between reference wavefront and the nominal aspheric shape. With the GDI method, W_{asp} is obtained as

$$W_{asp} \approx \frac{1}{2}W_{det} - W_{gdv}. \tag{1}$$

To simplify the calculation of W_{gdv}, spherical reference wavefront is usually employed in actual applications. Assuming that the shape of the nominal asphere and the reference wavefront is $f(\rho)$ and $S(\rho)$ respectively at the radial coordinate ρ, Eq. (1) is written as

$$W_{asp} \approx \frac{1}{2}W_{det} - \left[f(\rho) - S(\rho)\right]\cdot \cos\alpha(\rho), \tag{2}$$

where $\alpha(\rho)$ represents for the normal angle of the asphere. As shown in Eq. (2), besides the nominal shape of the tested asphere, priori knowledge of the algorithm is the curvature radius of the spherical reference wavefront. It must be said that this algorithm is based on the assumption that the imaging system is perfect. Or in the strict sense, it solves the non-null problem the way of a null configuration.

2.2. The TRW method

Retrace error has much to do with the system structure, since most reflected rays propagate through parts of the optical elements that are different from those of the incident. Understanding how rays propagate in the system helps with a further correction. Aided by ray tracing program, interferometric system is able to be modeled and calibrated for a "white box" system to show the light paths of both the reference and test waves. Retrace error is corrected with the TRW method by ray tracing the interferometric system model once.

Suppose the actual system has been modeled and calibrated in a ray tracing program, in which the test part is modeled with its nominal shape. After ray tracing the model once, OPD on the image plane can be obtained, noted as W'_{det}. W'_{det} is called the theoretical wavefront, which expresses the inherent retrace error of the system. Since the model is according to the actual system, W_{det} on the detector deforms from W'_{det} due to the existence of the aspheric figure error to be tested. This situation is similar to a null test [18]. According to the coherence testing principle, aspheric figure error can be obtained as