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High-precision spherical subaperture stitching interferometry based on digital holography

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A B S T R A C T

A novel subaperture stitching interferometry is proposed to measure the high-numerical-aperture sphericity for workshop testing, which combined digital holographic technology, subaperture stitching algorithm and systemic aberration calibration. Each subaperture is fleetly measured by the digital off-axis holography with a single shot so that the influence of measurement environment can be effectively reduced. The high-precision full aperture shape is obtained by stitching these subapertures, meanwhile, the subaperture alignment errors and the systemic aberration can be correctly compensated by the method of least-squares with the Zernike polynomial fitting. The approach is verified by testing three spherical surfaces, including a concave sphere, a convex sphere, and a hemisphere, in general environment. Moreover, the measurement results are compared with full aperture results by using a large aperture interferometer of Zygo and stitching result by using a subaperture stitching interferometer of QED. The results based on the proposed approach are consistent with the commercial interferometers. Specifically, the relative deviations of RMS are 0.009 λ and 0.02 λ for testing a concave and a convex spheres, and that is 0.011 λ for testing a hemisphere. Our method not only has the comparable measurement accuracy with the commercial interferometers but also is more robust, feasibility and inexpensive than other subaperture stitching interferometry. We provide an anti-interference way to test spherical surfaces in workshop environment.

1. Introduction

Spherical optical elements with high-numerical-aperture (NA) can find more applications in modern optical systems such as cameras, lithographic lens [1] and space observation. The corresponding surface test technique is a key factor restricting the machining accuracy and efficiency. The spherical surface is usually measured in a null test configuration with a standard interferometer, in which the center of curvature of the test surface coincides with the focus of the transmission sphere. However, due to the limitation of aperture or f/number of the transmission sphere, the high NA spheres such as hemisphere cannot be tested in a single measurement. Therefore, subaperture stitching interferometry (SSI) has been proposed to extend the lateral measurement ranges and enhancing the lateral and vertical resolutions of a standard interferometer. In this technique, the full aperture is divided into a series of smaller subapertures, which can be tested in a single measurement [2]. Then, the full aperture map is obtained by splicing these subaperture measurements. At present, SSI plays an important role in large aperture and high NA surface metrology, including large planar [3], cylindrical [4], spherical [5], aspherical [6,7] and even free-form surfaces [8–10].

For getting all subaperture data, it is imperative to align each subaperture to the test beam. Due to the mechanical movement, the misalignment of subaperture will inevitably introduce and contribute to the subaperture wavefront aberrations, which couples with the surface error. To remove misalignment induced aberrations, the stitching algorithms has proposed to bring all subaperture measurements together by computing a correcting position correction for each sub-aperture. The earliest stitching algorithm was based on fitting polynomials to non-overlapping subapertures and used to measure large optical flats [11]. To improve the splicing accuracy, the stitching algorithms was improved by mathematically minimizing the mismatch among the overlapping areas of multiple subapertures [12]. Subsequently, Sjodahl et al. [13] proposed an iterative splicing algorithm based on the global optimization theory to reduce the positioning accuracy requirements. Tang et al. [14] developed a stitching algorithm for multi-degree of freedom misalignments correction by fitting the phase deviation of the points in subaperture overlapping region. Furtherly, Chen et al. [15] provided stitching iterative algorithm based on the alternating optimization technique and the successive linearization method. Recently, Yan et al. [16] presented an iterative triangulation stitching algorithm to resolve the errors accumulation in the iterative calculation. Furthermore, to improve measurement accuracy, the system error including the reference mirror error and instrument error should be removed from the subaperture measurements. In fact, these errors could be calibrated by absolute testing [17–20], such as N-position testing, pseudo shearing and random average tests. However, these methods need standard optical elements or complicated operations, which are time consuming and may intro-

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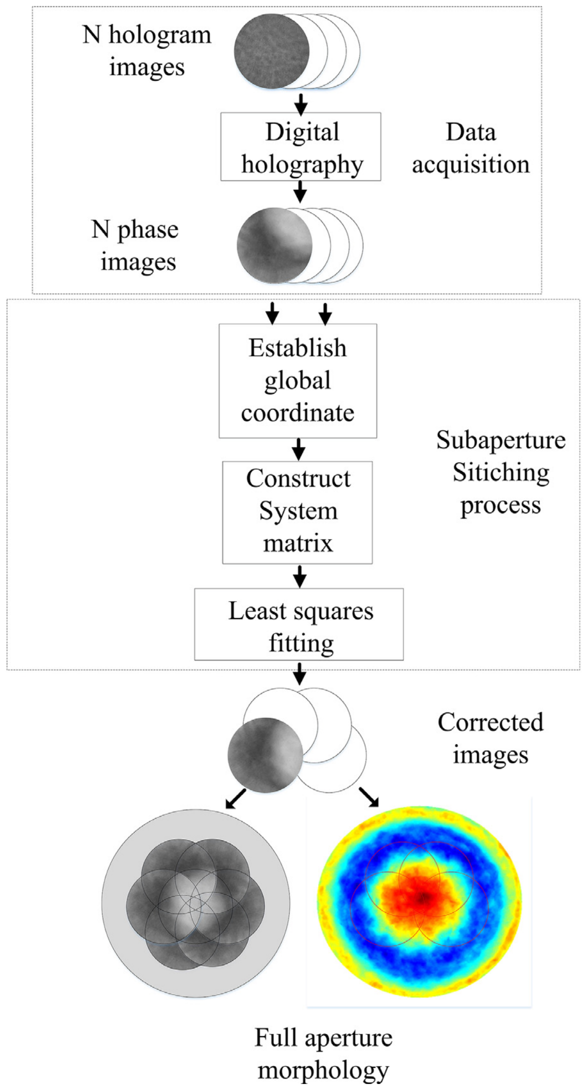

Fig. 1. Flowchart of subaperture stitching process.

duce other errors. Thanks to the system error is predictable and identical in every subaperture, it can be identified and corrected from subaperture data. Lin et al. [21] proposed high-overlapping-density subaperture stitching method to reduce the impact of reference errors. Maurer [22] provided a self-calibrating stitching algorithm to calculate the reference error by fitting polynomials. Furthermore, QED [23] presented a stitching algorithm which not only can compensate for the positioning error but also self-calibrate the reference error. So far, however, most of SSI is based on a standard interferometer, which is sensitive to the environmental influence of workshop. So, the environment and the entire system must be stable during the measurement process. In recent years, the dynamic interferometer can apply and achieve measurements in harsh environment [24]. However, such interferometer requires more complex process technology and high cost. In recent years, the digital holography combined different techniques have been widely used in topography measurement, such as Christophe et al. [25] have measured the topography of micro-components with large height steps by using multiwavelength illuminations. Vít et al. [26] have obtained the morphology of objects with complex composite structures by sweeping the frequency of source. Ichirou et al. [27] have achieved topography measurement by combining phase-shifting technology and dual wavelength illuminations. Jun et al. [28] have retrieved the topography of object by using lensless Fourier Holography with multi-illumination. In our previous works, we proposed a subaperture stitching interferometry based on digital holography (DH) [29], which can reduce the impact of environment uncertainty by quickly getting subaperture data. In this technique, the subaperture phase is acquired by DH and the fullaperture map are obtained by combining holographic reconstructing and subaperture stitching algorithm [30,31].

In this paper, we proposed a high-efficiency and high-precision digital holographic subaperture stitching interferometry (DH-SSI). Similarly, to the method [29], the phase map of subapertures are obtained by using off-axis digital holography. The difference is that an optimizing stitching strategy is presented to compensate the subaperture alignment errors and the system optical aberration. The stitching process is based on the holographic reconstruction and Zernike polymerization. First, the subaperture phase map is obtained without misalignment error by digital aberration compensation in holographic reconstruction. Second, the full aperture phase map is spliced with compensating system optical aberration and residual misalignment error by Zernike polynomial least-squares fitting. The basic principle of measurement and strategy of stitching are introduced in Section 2. Furthermore, the different spherical component is tested and analyzed to verify the proposed method, as described in Section 3. Section 4 summarizes the conclusions.

2. Methods

The flowchart of the proposed method is shown in Fig. 1. First, the holograms of subapertures are sequentially recorded. Then the phase maps of subapertures are retrieved by digital holographic reconstruction, while the low order aberrations due to the misalignment errors are corrected by numerical aberration compensation method. Subsequently, an appropriate stitching strategy is proposed on the basis of Zernike polynomial least-squares fitting for removing the optical system error and residual subaperture misalignment error. Finally, the full surface phase shape is obtained by stitching all subaperture phase maps.

2.1. Data acquisition

The subaperture data is obtained by off-axis digital holography. In this process, the tested spherical element is held on a multi-degree of freedom stage. The layout of the experimental setup is shown in Fig. 2 and like the Ref. [25]. A He-Ne laser (632.8 nm, 5 mW) is used as the light source. The combination of a polarizing beam splitter (PBS) and a half-wave plate ($\lambda/2$) is used for the adjustment of the intensity ratio of the beam in the reference arm and the object arm. Beam expanders (BE1, BE2) are incorporated to produce plane waves. The custom-made complex lens (CL) with a high NA (0.70) produces a converging spherical wave with a peak-to-valley (PV) less than 1/10 ($\lambda = 632.8$ nm). The CL includes a 5x beam expander and a convergent lens with an aperture angle of 86.3°. The horizontal distance is 30 mm between the focal point and the face of the lens. The diameter of the outgoing beam at the face of the CL is 58 mm. Based on null configuration, the center of curvature of the tested surface is positioned to coincide with the focus of the spherical wave emanating from the CL. So, the spherical wave can be perpendicularly incident on the spherical surface and the reflected light can return along with the original path. Therefore, the reflected wave, which called the object wave, provides information about the figure and the irregularity of tested surface. The object wave O and the reference wave R are recombined by a BS and interfere at the camera surface, and then the hologram is recorded by CMOS camera (the resolution of 2048×2048 pixels, the pixel size of $5.5 \times 5.5\,\mu$m) and transmitted to a computer.

2.2. Subaperture stitching process

2.2.1. Establish a global coordinate system

For synthesizing all subaperture, the global coordinate system must be established. The process can be divided into three steps. First, the subaperture local coordinates are calculated according to the system