EXTENDING THE ACCURACY AND RANGE OF AN INTERFEROMETER THROUGH SUBAPERTURE STITCHING

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Abstract

Subaperture stitching is a well-known technique for extending the effective aperture and dynamic range of phase measuring instruments. Several commercially available interferometers can automatically stitch flat surfaces, but practical solutions for stitching spherical and aspherical surfaces are inherently more complex. We have developed an interferometer workstation that can perform high-accuracy automated subaperture stitching of spheres, flats, and mild aspheres up to 280 mm in diameter. The Subaperture Stitching Interferometer (SSI®) workstation combines a six-axis precision stage system, a commercial Fizeau interferometer of 4" or 6" aperture, and a specially developed software package that automates measurement design, subaperture data acquisition, and the mathematical reconstruction of a full-aperture phase map. The stitching algorithms automatically compensates not only for positioning errors caused by the stage mechanics, but also for systematic errors such as imaging distortion and reference wave. Methods for calibrating systematic errors are discussed, and our ability to perform absolute measurements is analyzed. We present SSI stitched data, and compare stitched measurements to a calibrated full-aperture measurement.

Keywords: Interferometry, subaperture stitching, SSI, error compensation, absolute calibration

1. Introduction

1.1 Subaperture stitching background

Interferometry remains a key technology for precision optical surface metrology. The reproducibility, accuracy, spatial resolution, vertical resolution, speed, and flexibility of interferometer technology have continuously improved to support the increasing demands of the optical manufacturing industry. However, the basic geometry of optical surface testing and the limited slope measurement capability present technical and cost challenges to the measurement of optical surfaces of large physical dimension, high numerical aperture, and/or significant deviation from planarity or sphericity.

Subaperture stitching was primarily developed to overcome the aperture size limitations of conventional interferometry. Large aperture interferometers and transmission spheres often have prohibitively high costs and/or long lead times, so stitching is an attractive alternative. It involves synthesizing a full-aperture phase map from multiple subaperture phase maps by combining an interferometer with motion capability and a stitching algorithm. The earliest stitching methods were able to determine only the low-order form of the surface by fitting polynomials to non-overlapping subapertures [1,2]. However, modern stitching algorithms are able to achieve high spatial resolutions as well by mathematically minimizing the mismatch among the overlapping subaperture areas. Simple overlapped stitching algorithms combined subapertures sequentially. A significant improvement, however, was achieved by *simultaneously* optimizing alignment terms among *multiple overlapping* subapertures [3]. Lateral geometry calibration was used to improve the quality of stitched reconstructions by compensating for mechanical positioning uncertainties of subapertures in a stitching microscope interferometer [4]. These developments extended an interferometer's effective lateral coverage for flat surfaces.

1.2 Subaperture stitching motivation

Interferometry systems that provide automated stitching of flat surfaces of small [5] and large lateral dimension [6] are commercially available. None of these systems, however, address the need for stitching large aperture spherical optics, particularly those of high numerical aperture (e.g. domes). Figure 1 illustrates parts of various aperture and radius combinations that can—and cannot—be fully covered by a standard 4" interferometer. Notice that stitching fills a significant gap in high numerical aperture capability, as well as longer radius convex parts that would otherwise require a large-aperture interferometer and custom transmission spheres.

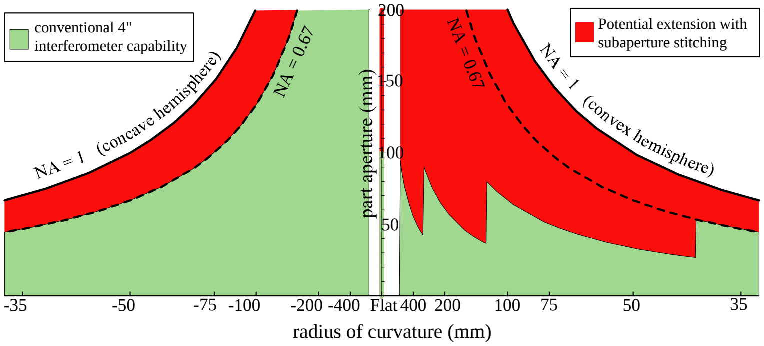


Figure 1: Full aperture capability of a standard 4” interferometer (including 4 transmission spheres and a transmission flat), and the expanded capability of a stitching interferometer.

The capability gap is considerable. In fact, there is a significant number of optics less than 50 mm in diameter that cannot be measured with a standard 4” interferometer. Large aperture convex parts (50 to 200 mm or so) could be tested with a large aperture interferometer and transmission spheres. The costs of such systems, however, are extreme. Furthermore, large aperture interferometers are not really any more capable of testing high numerical apertures. Instead of measuring the entire aperture of the part, manufacturers commonly measure only the portion they can “see” with their interferometer, and assume that the rest of the part is no worse. Sometimes another subaperture measurement is taken at the edge of the test part, to “make sure” the rest of the part is in fact no worse.

Such methods, however, have two major flaws. The first is that advanced deterministic finishing techniques (such as magneto-rheological finishing) require full aperture metrology. Therefore the lack of full aperture metrology prevents leveraging such processes to obtain cost-effective surfaces of extremely good quality. The second is that subaperture quality is a necessary but *not sufficient* condition for full aperture quality.

1.3 Subaperture Stitching Interferometer (SSI) system description

QED has developed the SSI to provide a commercially viable capability for full-aperture measurement of larger aperture (up to 280 mm) convex parts and high numerical aperture parts (domes) [7,8]. Figure 2 shows some examples of parts that cannot be full aperture tested on a conventional 4” or 6” interferometer, but are easily handled by the SSI. It also adds the potential for measuring aspherical surfaces of modest departure. The SSI is a breakthrough marriage of three technologies: interferometry, precision motion control, and advanced mathematics. A commercial 4” or 6” interferometer is mounted on a six-axis workstation engineered in cooperation with Schneider Opticmachines [9] as shown in Figure 3. The interferometer is a standard Zygo Fizeau interferometer [10], and is mounted in a down-looking configuration atop the X/Y stage. It is remotely controlled to integrate seamlessly with the motion control, enabling automatic acquisition (including fringe nulling) of all the subaperture data. Special software automatically coordinates the measurement design, data acquisition, and mathematical analysis of the stitching process.

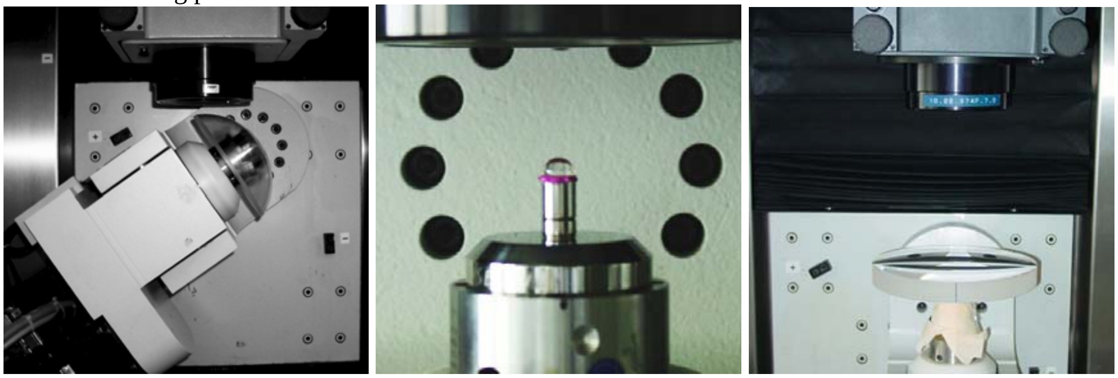

(a) (b) (c)

Figure 2: The SSI is able to measure surfaces of large NA and CA – (a) Dome: diameter 148 mm, radius 82 mm (large NA and CA); (b) hemisphere: radius 4.45 mm (large NA), and (c) convex: diameter 200 mm, radius 500 mm (large CA)

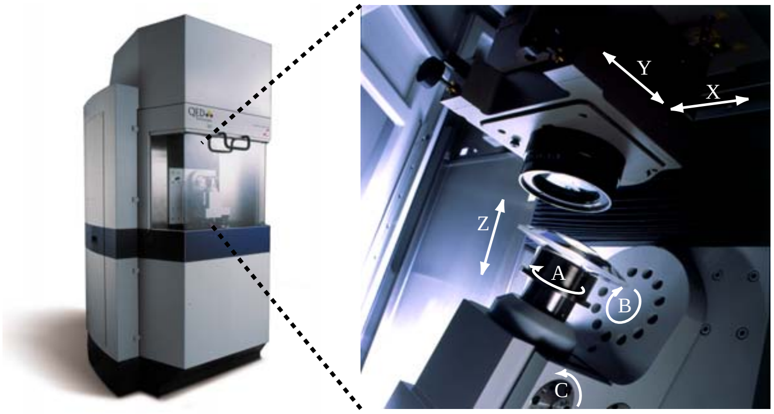


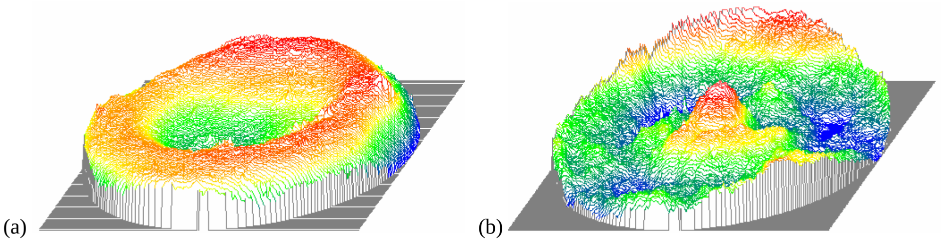
Figure 3: SSI workstation with stage axes labeled.

2. High Accuracy Stitching Example

In order to obtain confidence that the stitching is accurate, QED has compared many stitched measurements against calibrated full-aperture measurements. One such test is demonstrated in the following subsections. The part under test is concave, radius of curvature 126 mm, with a full aperture of 80 mm—and can thus be easily full aperture tested.

2.1 Full-aperture measurement

One well-known method for separating reference wave error from the surface error is the two-sphere procedure. [11,12]. This procedure uses four confocal measurements with 90° rotations of the surface between measurements, and a cat's eye measurement. Figure 4 shows the results of the two sphere test: (a) the test surface and (b) the reference surface.



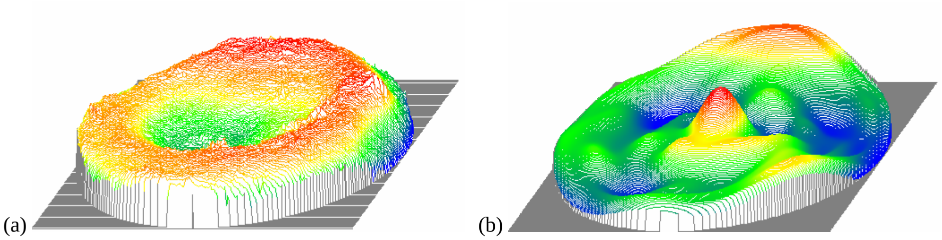
rms: 8.7 nm

rms: 3.9 nm

Figure 4: Results of two-sphere measurement: the (a) test surface and (b) reference surface. The measurement scale is PV 20 nm.

2.2 Stitched measurement

The same surface was measured on the same interferometer, but by stitching 5 subapertures together and using a calculated reference wave. The stitching calculated the reference surface from the subaperture data itself by independently optimizing the values of 230 Zernike polynomial terms (no special calibration was needed). Figure 5 gives the results of this test. The rms of the difference between the two-sphere (Figure 4a) and stitched test surface (Figure 5a) is about 1 nanometer. Note that this was achieved under shop floor conditions without any special temperature control.



rms: 8.2 nm

rms: 3.4 nm

Figure 5: Results of a stitched measurement: the (a) test surface and (b) SSI calculated reference surface (represented by 230 Zernike polynomial terms). The measurement scale is PV 20 nm.

3. Conclusions

The SSI significantly enhances commercially available aperture and accuracy capability. High numerical aperture parts such as domes can now easily be measured over their full aperture. Not only does this eliminate the need for inaccurate subaperture extrapolation, it also enables manufacture of domes to unprecedented quality with deterministic finishing methods such as MRF [14]. Stitching can also extend mild aspheric measurement capability from a few micrometers to tens of micrometers of departure from best-fit sphere without the use of any null optics. Further developments will include removal of the nominal shape, cross-testing with other measurement methods, and additional automation.

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