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High precision interferometric measurement of freeform surfaces from the well-defined sub-aperture surface profiles

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We report an interferometric method for smooth freeform optics from the amount of sub-aperture surface profiles. The overall experimental system is composed of a 5-axis precision stage and a sub-aperture measuring interferometer, which is carefully calibrated to achieve 2 nmRMS precision. The sub-aperture interferometer adopts a broadband source in order to maximize the reliability of profile measurement, and a preliminary assumption of the overall surface is derived from the measured local 2nd derivatives which is robust to tip/tilt alignment errors during the sub-aperture acquisition. The optical surface of a 200 mm diameter 2D polynomial freeform mirror is measured based on this system and traditional contact surface profiler for the cross-validation. The experiment shows the effectiveness of the system that the mismatch against a commercial interferometer is less than 20 nmRMS.

NOMENCLATURE

a = directional orientation of the system
h = strip thickness with strip thickness and strip thickness strip thickness

1. Introduction

Sub-aperture stitching interferometry is a technique introduced to extend the measurable aperture of traditional interferometers1,2, however, this technique has recently been recognized for its potential to measure aspherical and freeform surfaces without optical nulling components3.

The measuring equipment to be developed in this research project is a general-purpose device that can measure non-spherical or freeform optical surfaces in a non-contact manner, and uses a sub-aperture stitching method that measures and joins three-dimensional profiles of the sub-apertures. By combining the height profile, slope, and radius of curvature of the local region, the free-form surface measurement region of arbitrary shape aims to restore the entire optical surface to the final measurement accuracy of $\lambda/20$ or less, targeting a large diameter of 600 mm or less. In order to realize this concept, we developed a multi-axis degree of freedom ultra-precision feeder system that enables precise positioning of an interferometric probe upon tens of sub-apertures, and verified the measurement system with some aspheric and freeform optical surfaces.

2. Sub-Aperture Stitching Interferometry Principles

A spherical or plane surface which is mainly used for traditional optical lens shapes has single constant curvature value over the entire clear aperture. However, in the case of aspherical surface, which has recently been dramatically increased in utilization, the local curvature of the surface changes continuously with circular symmetry according to the distance from the optical axis. Since the reference shape or curvature is unclear and the interference pattern is extremely dense, the conventional interferometric method is hardly applicable without some nulling schematics.

In order to measure the aspherical or freeform surfaces, we divide the entire aperture into tens or hundreds of sur-apertures optimized for the designed surface shape and collects three-dimensional height profile of each area to restore the shape of the optical surface. Figure

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1 below shows the brief strategy of sub-aperture stitching technique developed in this project. First, a part of the entire surface is designated to obtain a three-dimensional height profile by using an interferometric probe, and the curvatures of two orthogonal directions are extracted from the obtained shape by circular shape fitting or Zernike polynomial fitting. The curvatures thus obtained are arranged in a determinant according to the position of the sub-apertures and replaced by the gradient matrix at each point through the curvature-slope relation such as Frenet's equation. Finally, the wavefront estimation is performed using the Southwell or Simpson method based on the obtained gradient matrix, 3D surface profile can be reconstructed through the entire clear aperture[4].

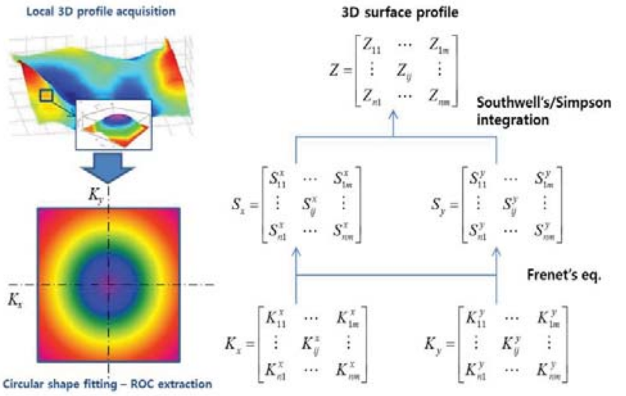

Fig. 1 Conceptual diagram for 3D surface reconstruction method by measuring sub-aperture curvature profile

3. Experimental Setup

3.1 Interferometric Probe

For measuring a aspheric or freeform surface, we need the well-defined reference surfaces and an optimized illumination system according to the designed sub-apertures. In particular, the measurement accuracy of the sub-aperture stitching interferometer cannot exceed the measurement accuracy of the interference probe mounted on the equipment, so that techniques such as self-calibration can be applied to improve the accuracy, and very low alignment uncertainty of various types of wavefronts. Requires special optical probe that can be generated

Figure 2 outlines the optical layout of the designed interference probe. The first prototype of the interference probe was developed by constructing a commercial beam expander in a stabilized He-Ne Laser light source for ease of configuration. The optical system is configured as a modified Twymann-Green interferometer, in which a replaceable reference mirror, and a zooming illuminator are employed to minimize the effects of radius of curvature while providing uniform illumination in the desired area. The imaging lens and CCD camera gives the measuring area of about 45 mm x 45 mm, and the minimum measurable curvature is designed to be about 60 mm or less. For the exact phase acquisition, the reference mirror is mounted on a PZT stage. Before the actual measurement, the shape of reference plane can be calibrated precisely by averaging in tens of random positions and orientations.

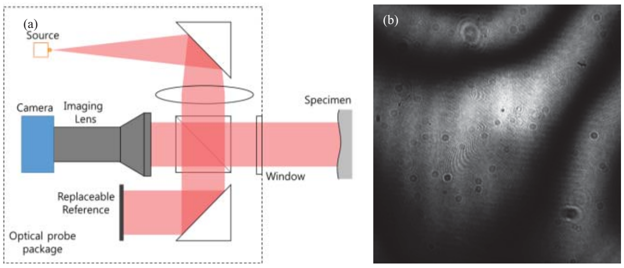

Fig. 2 Optical layout of an interference probe prototype, (a) with plano reference and (b) concave reference

3.2 Precision Positioning Stage

The preliminary structural analysis of the multi-axis high-precision feed system that enables precise positioning for various sub-apertures in the freeform surface was carried out by mounting the designed interference probe. The precision stage is designed with 5 axes of X / Y (700 mm travel), Z (400 mm travel), A / B(±20 deg) and C (360 deg), and the positioning precision is less than 10 μm for the linear translation motion. For the basic analysis of the stage assembly, modeling was conducted on the structural analysis program, and the simulation was performed under the condition of applying 50 kg of load on the Z axis. The deformation and natural frequency analysis satisfies the requirements of the high precision feed system with the maximum deformation of 10 μm, which was below the positioning accuracy of the stage, and the natural frequency in the first mode is 111 Hz, which operates in a stable region.

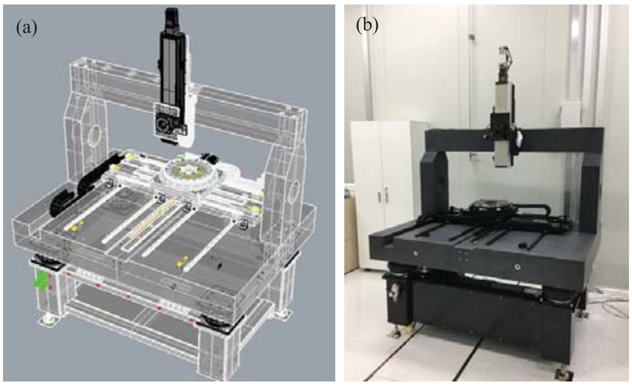

Fig. 3 (a) Design of a high precision stage system, (b) an actual prototype

4. Results and Analysis

In order to verify the developed system, a 300 mm diameter flat mirror was measured as shown in Figure 4. The entire surface profile was measured by the developed system and a commercial interferometer, and the difference was mapped by linear interpolation. The difference between two systems were 16.5 nm in RMS value, and it was less than the guaranteed surface precision of the commercial reference flat.

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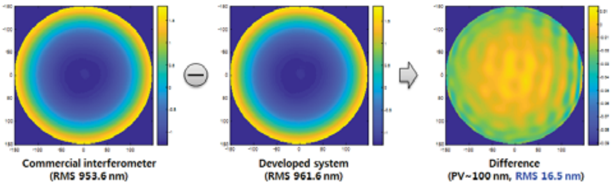
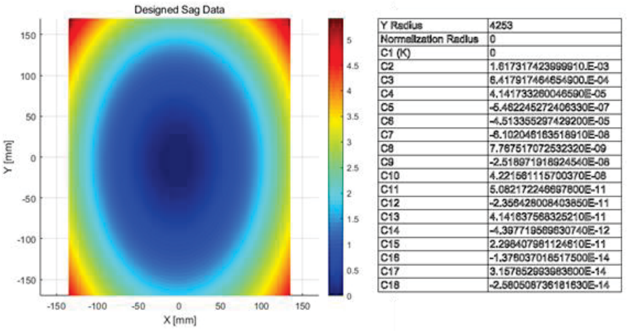


Fig. 4 Experimental results on the aspheric surface measurement

In order to verify the freeform measurement capability, a reflective optical system is manufactured as shown in Figure 5. The optical system is 240mm wide and 228mm long with a diagonal length of 303mm and the surface shape is XY polynomial freeform with 10th order coefficients. Verification using the test freeform phase was conducted by comparing the measurement results using the conventional commercialized equipment, the atomic force three-dimensional shape profiler (UA3P, Panasonic) with the results of the freeform phase detector developed in this project.



Y Radius	4253
Normalization Radius	0
C1 (K)	0
C2	1.617317423999910.E-03
C3	6.417917464654900.E-04
C4	4.141733260046590E-05
C5	-5.462245272406330E-07
C6	-4.513355297429200E-05
C7	-6.102046163518910E-08
C8	7.767517072532320E-09
C9	-2.518971918924540E-08
C10	4.221561115700370E-08
C11	5.082172246697800E-11
C12	-2.356428008403850E-11
C13	4.141637568325210E-11
C14	-4.397719569630740E-12
C15	2.298407981124610E-11
C16	-1.376037018517500E-14
C17	3.157852993983600E-14
C18	-2.580508736181630E-14

Figure 5. The design parameters and a sag map of measuring freeform reflective optical system

The free curved surface used for verification was impossible to measure shape because the interference pattern could not be obtained by the general laser interferometer, and it could be compared only by the contact shape measuring device and the equipment developed in this project. It was confirmed that the measurement results through the conventional commercialized contact profiler and the freeform measurement system developed in this project were almost identical. In the quantitative comparison with commercial equipment, only the measurement result on a predetermined path can be obtained, and the free-form measuring device compares the measurement result in the entire free-form area with the contact measuring device, which cannot accurately align the stylus path with the outer diameter of the reflector. The figure error of the freeform surface is measured as 0.154 um RMS with the contact profiler and 0.151 um RMS with the developed system. According to the difference of the above measurement methods, it is difficult to compare the two measured values in a 1: 1 ratio, but it is a result that it can be seen that it has secured a very similar level of accuracy.

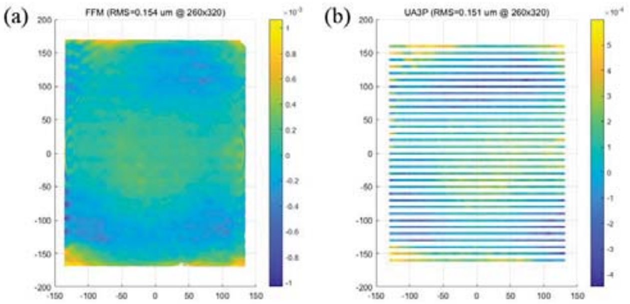


Figure 6. Surface irregularity map measured by (a) the developed system and (b) the commercial 3D profiler

5. Conclusion

We have constructed an asphere/freeform measuring machine based on the sub-aperture stitching interferometry. The machine verification was performed against some optical surfaces and the figure error deviation with commercial devices was less than 20 nm RMS. A freeform surface, which configured with 2D polynomial with 10th coefficients, was measured with developed system and a commercial contact profiler, and the measurement results gives good convergence overall entire clear aperture.

ACKNOWLEDGEMENT

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