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Stitching Interferometry for the Measurement of Aspheric Surfaces

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Abstract

In this paper, we describe the progress being made in the development of stitching interferometry for measuring curved surfaces with large aspheric departures. Stitching interferometry is an extension of conventional interferometry by making a series of submeasurements and then stitching the surface segments together to obtain an entire reconstructed surface. We have implemented it by modifying a phase shifting interferometer with a mechanical manipulator for shifting and/or rotating the workpieces under test precisely. An outline summarising the principles and the algorithms developed, to correct the aberrations introduced by the misalignment of the submeasurements and the misregistration of the individual data sets, is presented. The technique offers considerable potential applications for testing precision surfaces with large aspheric departures.

Key words: interferometry, aspheric optical surface, measurement

1 - Introduction

Aspheric surfaces have been more and more used or suggested for application in a variety of fields^{7,9}. The use of lenses, mirrors and precision products with aspheric surfaces, as well as with other kinds of curved surfaces is increasing with required high precision. As examples we mention contact lenses, objectives used in compact disc players and in many kinds of recorders, precision workpieces with aspheric surfaces employed in diverse precision machines and astronomical equipment.

Aspheric surfaces are often manufactured by CNC controlled machines based on precision processes. Therefore, precision measurement of such kind of curved shapes is a necessity for manufacturing process control and product quality validation. However, there have been yet limitations in using aspheric elements. Metrology determines mostly the difficulty. For precision topography measurements on aspheric surfaces, classic interferometers are often not suitable because of a too high fringe density and aberrations due to the aspheric departures^{3,4,5,6}.

The aim of this research is to develop a suitable method for aspheric shape testing with a submicron accuracy range (The term "submicron" in this paper means a few tenths of a micrometer). We think that a good choice is to use phase shifting interferometry with manipulating the object under test versus the reference surface accurately. We have developed such a measurement technique, named "Stitching Interferometry", by modifying and utilising a phase shifting interferometer with a mechanical manipulator for adjusting workpieces under test precisely.

The key points of our technique are the following. First, unlike existing interferometers that employ only one reference wavefront with fixed configuration parameters in a measurement, we employ a family of wavefronts of reference with variable configuration parameters, by means of varying the relative position of the tested surface in respect to the reference surface. Another key point is that we first interpret sub-interferograms into geometrical topographies and then stitch the topographic segments up together to obtain the overall shape of a surface.

2 - Principles

2.1 The Aspheric Surface Tested

We have tested some aspheric contact lenses. However, a type of half-completed lenses with the most important interior surface being ready shaped, so-called buttons, were the objects tested most frequently. Such a lens inner surface is machined with an ultra-precision diamond turning machine, with a resulting shape accuracy PV (peak-to-valley) of submicrons and a surface roughness R_a of about 15 nanometers. The aspheric departures in the normal direction range from 25 up to 150 micrometers, corresponding to approximate 80 to 500 fringes.

The geometry of the lens or button can be divided into several different diametrical zones. Each zone can then be specified as a surface of revolution that can be mathematically described. These surfaces may range from spheres to aspheres that can be described by ellipses and polynomials. The aspheric inner surface of the contact lens is composed of four different kinds of surfaces. Figure 1 shows the shape of its axial cross-section. Please note that the segment B, the most important part, is not simply described by one definite ellipse but by a

family of varying ellipses, with variable parameters of eccentricity.

Fig.1 Axial cross-section of the inner surface of a contact lens
A: part of a circle; B: composition of varying ellipses; C and D: parts of two different polynomials.

2.2 Interferometry of Curved Surfaces

The interferometer used is a Fizeau phase shifting interferometer, shown schematically in figure 2. The laser beam is collimated after being expanded; beams from the reference surface and the object under test return through the collimator and related optics. They are then imaged on the CCD detector.

Fig.2 Schematic of Fizeau interferometry

2.3 Problem Description

With modern commercial interferometers, high precision measurements can be made of flats and spheres.^{3,7} However, the interferometric measurement of aspheric surfaces may be hard to perform. The problem is that, if the aspheric surface has a large departure of slope from the best fitting reference surface, an interferogram acquired without some sort of aspheric null elements contains too many fringes to be detected^{4,5,6}. In other words, such an interferogram is unresolvable.

Fig.3 Simulated interferogram of an elliptical surface tested at its vertex centre of curvature

Figure 3 illustrates the simulated interferogram of the same elliptical surface as segment B of the contact lens we tested, where the sampling density of points is 40x40 over the picture. It can be seen that frequencies above the Nyquist frequency of the CCD array are aliased in the outer zone of the interferogram.

2.4 The Stitching Strategy

After having analysed the interferograms of aspheric surfaces carefully, we found that even in the case of too many fringes, the interferograms of the aspheric surfaces can still be partially resolvable by splitting up the measurement in certain different zones. Where and whether the fringe density is resolvable depends directly on the shape of the test curved surface as well as the position of the object in the measuring frame, in respect to a certain CCD array.

Figure 4 and figure 5 intuitively illustrate the concept of stitching interferometry and the corresponding simulation results, respectively. The basic idea behind the stitching interferometry is to divide the wavefront or the measured surface up into several segments so that the fringe density over a sub-interferogram from each sub-measurement remains resolvable. In other words, to shift the object with respect to the reference surface, such that the differences in angle between the reference wavefronts and the tested surface will be minimised.

Fig.4 Comparing an aspheric surface(thick) with reference wavefronts(thin) varying in radius

Fig.5 Simulated interferograms with object position shifting from the vertex centre of curvature

To accept the strategy implies that instead of using only one reference wavefront with fixed configuration parameters, a family of those, with variable configuration parameters such as radii, positions and orientations, must be employed.

We describe the stitching procedure as follows. We record two interferograms of the object in two positions in space (figure 6), in such a way that the two pictures have a surface region in common where the fringes are well resolved. Between the two positions, the object under test is shifted. From these two interferograms, we calculate the surface profile in the two positions. We now can superpose the two surface profiles in the region of overlap, provided that we know the transformation between these two positions. Applying this procedure

recursively, a completely reconstructed surface can be acquired.

Fig.6 Stitching strategy

3 - The Stitching Algorithms

3.1 The Stitching Procedure

The first step of the stitching interferometry procedure is to shift the aspheric object from the focus of a reference sphere, such that every portion of the measured interferogram should be resolvable in turn. In this way, the entire surface is "swept" outwardly or transversally with certain predetermined overlapping sectors. As a result, a series of sub-interferograms from the sequential submeasurements is obtained. Additionally, it is important to determine beforehand the optimum intervals for manipulating the object under test. This is fulfilled by applying a so-called "penalty function" algorithm of optimization¹¹ to the measuring processing. Successively, transferring interferograms of submeasurements, beforehand, into topographical contours is a necessity. The final task is to stitch the topo-graphical segments together with much care to remove shape distortion owing to misalignments and aberrations owing to optical path variance.

Suppose P_i ($i \in N=[1,2,\dots,n]$) and Q_j ($j \in N=[1,2,\dots,n]$) be the data sets obtained from two consecutive submeasurements. Because of the aspheric departures of the surface and the position changes, there would be a misregistration of the data sets on the image grid, so $i \neq j$. After correction of the misregistration (see section 3.2), we acquire P_i and Q_j with the same data registration. Now we want to correct the distortion owing to the misalignments introduced by object position shift (see section 3.3). Finally, after doing that, we acquire two corrected data sets P_i and Q_j that represent the two adjacent topographical segments with a common region of overlap.

3.2 Aberration Correction of Image Formation

In the case of an aspheric surface being measured in the scheme of figure 2, the returning beams from the aspheric surface no longer follow the same path as in the case of a sphere. Therefore, the returning

rays do not pass through the focal point. Furthermore, owing to the object position changes, e.g. from position 1 to position 2 in figure 7, the optical path or the image forming direction from the surface to the CCD image plane changes too. These two facts result in misregistration of the data sets in the full surface frame.

Based on our previous work on the treatment of image formation by the use of Hamilton's method¹⁰, we have solved the problem by means of the eikonal methods¹. These methods deal with the derivative characteristic functions of a surface and enable us to determine uniquely the corresponding image position of a surface. We assume that the optical system is linear, i.e. no aberrations.

Fig.7 Optical path changes

By analysing the geometry of the tested aspheric surface, we can obtain focus offsets and slope changes, or direction cosines, l, m, n , for each point on the surface, see figure 7. We then use paraxial equations^{1,7} to calculate direction cosines of the imaging beams, l', m', n' . Also, we must calculate the shape of the aerial image surface, which is no longer a plane surface. As a result, we then finally know the compensation needed for correction of the misregistration.

3.3 Misalignment Correction

During two successive submeasurements, the position of the object changes. Therefore, a misalignment could be introduced although our self-designed manipulator possesses a quite nice sub-micron accuracy². The basic criterion for adjusting the measured segments is that they match each other as well as possible in the overlapping region. As for the two data groups of P_i and Q_j within a common overlap region, they should represent the same part of the tested surface. As a result, there should exist an adjustment such that the data points of second set Q_j are mapped on the first, P_i . Nevertheless, due to the measuring errors and the system aberrations, it is impossible to find a transformation that satisfies the condition for every point of Q_j and P_i . We have to solve an optimization problem, i.e., to find the "best" transformation that brings most of the points as close as possible to the surface.

The elements of such a transform matrix are infinitesimal, compared to the size of the measured ob-

jects, except for the translation along the optical axis. Accordingly, we could successfully take advantages of the robotics theory of differential transformations⁸ and some commercial computational software to correct the misalignments.

4 - Experimental Results

We have obtained good results not only of simulations but also of practical experiments. Figure 8 gives a group of experimental results of an aspheric contact lens by stitching interferometry. We first obtained the inner and outer portions of the aspheric surface (figure 8.a and 8.b) in two submeasurements respectively with a common region of overlap(figure 8.c), and then stitched them up to acquire an entire surface (figure 8.d).

Fig.8 Stitching up submeasurements

- a) inner portion (PV = 176 nm, RMS = 34 nm);
- b) outer portion (PV = 195 nm, RMS = 38 nm);
- c) two portions with overlap region(dark annulus); 232 nm, RMS = 39 nm);

Fig.9 Reconstructed overlap surfaces

- a) via the 1st submeasurement (PV = 127 nm);
- b) via the 2nd submeasurement (PV = 160 nm);
- c) corrected 2nd submeasurement (PV = 128 nm)

A beautiful result can be seen from figure 9 as a validation of the correction efficiency of the stitching algorithms.

The two data groups from the first submeasurement P_1 and the second Q_1 , respectively, should represent the same part of the overlap region. However, the topography from the second raw data set (figure 9.b) brings us a much different shape from that of the first one(figure 9.a), while the corrected data set does bring us an almost the same one (figure 9.c).

5 - Conclusions

Considering the good results and validated correctness, we believe that with stitching interferometry it is possible to measure the shape of complicated surfaces precisely. Currently, the method is used for rotational symmetric aspheric surfaces. We shall extend it to the asymmetric domain, for astigmatic lenses too.

We suppose that the concept and method are capable to upgrade an interferometer and can extend the measurement range up to several tens or even several hundreds of micrometers, to measure the departure of an aspheric surface from its base surface.

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