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Use of coordinate measuring machine to measure circular aperture complex optical surface

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ABSTRACT

The measurement of complex surface with form accuracy up to micrometers is of critical importance in the field of precision manufacturing and measuring. In this paper, a systematical measuring method based on coordinate measuring machine (CMM) was proposed for the circular aperture complex optical surface. By proposed method, concentric-circles discretized by equally spaced angle were chosen to obtain the sampling points, and the spline interpolation method for probe radius compensation was considered, then the compensated data points were fitted to measured surface using Zernike polynomials. Furthermore, a simulation of toric surface was studied to analyze surface construction error. Under specific parameter condition of discretization angle of 15°, step length of 1 mm and fitting terms of Zernike polynomials 66, the PV form error was 0.1596 μm and RMS was 0.0292 μm. The simulation results show that the proposed fitting method can meet the requirement of inspection accuracy at the micron level. Finally, a progressive addition lens complex surface was measured by a MQ686 CMM to verify the feasibility of the proposed method.

1. Introduction

Complex optical surface offers additional degrees of freeform to the designer to optimize performance, such as size reduction, structure reduction and image quality improvement [1]. These complex optical surfaces are today used in many applications including eyewear, electro-optics, defense, automotive and others [2]. Due to the complex non-rotationally symmetric property, complex optical surfaces are more difficult to fabricate than rotationally symmetric surfaces. Meanwhile, precision measuring is indispensable and usually coupled with the manufacturing process.

In accordance with different manufacturing phases, coordinate measuring machine (CMM), profilometer, optical interferometer and confocal microscopy are selected to measure complex optical surface. In the first phase of manufacturing process like precision turning or milling, the surface is turned/milled until the form error is at the micron level [3]. In general, CMM is preferred for this phase to meet the requirements of inspection accuracy, efficiency and cost. Numerous studies in the field of measurement of freeform features by CMM have been conducted in the past, including measuring path planning, sampling strategy, probe radius compensation, surface fitting and tolerance assessment. Obeidat and Raman [4] developed three algorithms for sampling of freeform surfaces at a patch scale. The three developed algorithms took each patch on the surface as a separate unit and distributed the points within the patch in two steps. The sampling algorithms helped to select an efficient number of sample points and to minimize sampling effort and measurement time. Rajamohan et al. [5] proposed two new strategies of sampling the points on the basis of curve length and dominant points considering the geometric nature of freeform profile. After the acquisition of the sampling points, the probe radius can be compensated by local approximation [6], surface fitting [7], matching the surface of probe centers to the offset of nominal surface [8], and direct approximation of the error caused by probe radius [9], etc. Then the actual contact points after probe radius compensation were fitted by B-spline [10], NURBS [1] or Zernike polynomials [11] to get the measured surface. Finally, the measured surface was compared with the design surface to determine the deviations. However, most of the measurement strategies were proposed for general freeform surfaces in previous studies, while limited information is available on measuring circular aperture complex optical surfaces.

Precision measuring is of critical importance in the field of machining complex optical surface. In this paper, a systematical measuring method is developed to measure the circular aperture complex optical surface with the form error at micron level effec-

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tively and economically. The concentric-circles discretized by equally spaced angle are chosen to plan the sampling points. Probe radius is compensated by spline interpolation method to get the actual contact points. Subsequently, the actual measured surface is obtained by Zernike polynomials fitting method and compared with the design surface to determine the surface error. Additionally, a simulation of toric surface is studied to analyze surface construction error using the proposed method. Finally, a progressive addition lens surface is measured to present a case study to prove the feasibility of the proposed method.

2. Measurement strategy

The general flowchart of measuring circular aperture complex surface is shown in Fig. 1. It consists of five building blocks, i.e. data acquisition, surface fitting using Zernike polynomials, probe radius compensation, surface comparison and measurement results. The data acquisition incorporates selection of measuring path, parameters setting and automatic measuring path generation. The obtained points representing the probe center trace are then fitted using Zernike polynomials. Subsequently, the probe center surface are compensated using tangent method or spline interpolation method to get the actual measured points. Furthermore, the fitting surface of actual measured surface is compared with the design surface to determine the deviations between them. The measurement results including 3D map of measured surface, 3D map of deviations, and PV and RSM values are exported finally.

The measurement was carried on a MQ686 CMM (Xi'an AEH Industrial Metrology Inc.) with a field of measurement $X \times Y \times Z$ equal to $600\ \text{mm} \times 800\ \text{mm} \times 600\ \text{mm}$ and with a measuring accuracy of 2.7 μm. The CMM was located in a temperature controlled room of 20 ± 0.2°.

3. Data acquisition

The measuring path plays an important role since it enables to make reasonable reference about surface error of a workpiece. An appropriate sampling strategy that should be able to provide adequate information about the measured surface as well as to reduce inspection cost and time has to be selected [12]. Considering the feature of circular aperture complex surface, the uniform section method was used to plan the measuring path, and the circle was chosen as the constraint face. Hence, the measured surface was divided into several concentric-circles with different radii. Furthermore, the measuring path was discretized by equally angle, as illustrated in Fig. 2. The acquisition of sampling points started from the peripheral lap of the concentric-circles with equally spaced angle $\Delta\theta$, and then moved toward the center to the subsequent lap as the radius decreased by step length Δl. This was repeated until the diameter of the central lap was less than Δl.

Compared with manual approach, parametric coded measurement (PCM) approach is advantageous to implement complex measuring path, improve measuring accuracy and efficiency. In this paper, the circular measuring path was realized through PCM off-line program by using the AC-DMIS software.

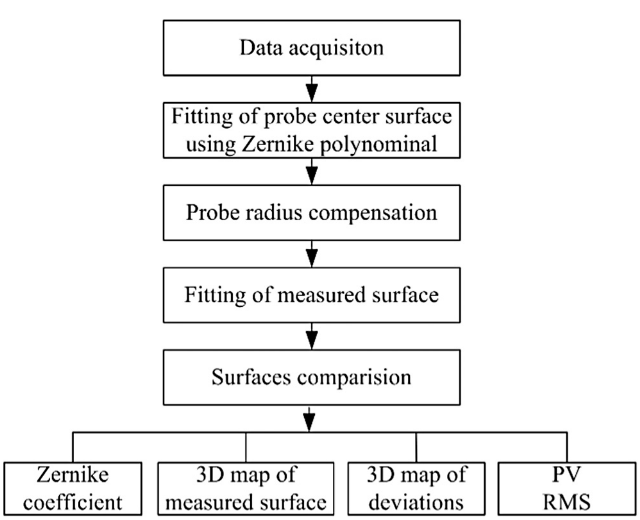

Fig. 1. Flowchart of measuring circular aperture complex surface.

4. Surface fitting using Zernike polynomials

4.1. Zernike polynomials

Zernike polynomials for circular aperture are useful for characterizing aberrations of an optical component, and have been successfully used in many fields of optics. Zernike polynomials are a set of orthogonal polynomials defined on a unit circle by the following equation [13]:

$$Z_n^m(\rho,\theta) = \begin{cases} N_n^m R_n^{|m|}(\rho)\cos(m\theta) & m \geqslant 0 \\ -N_n^m R_n^{|m|}(\rho)\sin(m\theta) & m < 0 \end{cases} \tag{1}$$

where the standardized coefficient N_n^m and the radial polynomial $R_n^{|m|}(\rho)$ are given as:

$$N_n^m = \begin{cases} \sqrt{2(n+1)} & m \neq 0 \\ \sqrt{n+1} & m = 0 \end{cases} \tag{2}$$

$$R_n^{|m|}(\rho) = \sum_{s=0}^{(n-|m|)/2} \frac{(-1)^s (n-s)!}{s!\left(\frac{n+m}{2}-s\right)!\left(\frac{n-m}{2}-s\right)!}\rho^{n-2s} \tag{3}$$

The indices n and m are the order of polynomial and azimuthal frequency respectively and should satisfy $|m| \leqslant n$, and $n - m = \text{even}$.

4.2. Fitting method

The sampling points obtained through CMM can be fitted using Zernike polynomials $Z_m^n(\rho,\theta)$ as:

$$\sum_{n=0}^{N}\sum_{m=-n}^{n} a_n^m Z_n^m(\rho,\theta) = z \tag{4}$$

where a_n^m represents the Zernike coefficients, N is the total items of Zernike polynomials and $0 \leqslant r \leqslant 1$ and $0 \leqslant \theta \leqslant 2\pi$. The sampling

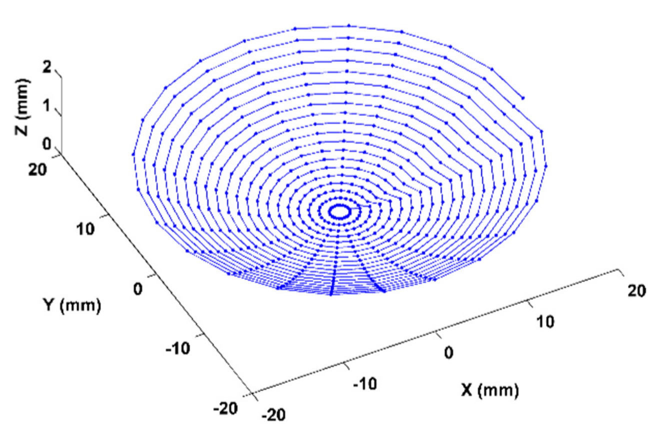

Fig. 2. Inspecting path of circle.