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Error analysis and surface reconstruction for swing arm profilometry

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ABSTRACT

Aiming to develop a prototype swing arm profilometer for several meter-class aspheres, we first present detailed error analysis including error motions of the swing rotary table and the part rotary table, and misalignment of the axes of the two rotary tables. The induced probing error in the normal direction of the reference sphere is calculated by considering the error motions in the coordinate transformation. A surface reconstruction algorithm is then proposed to separate the error motions of the part rotary table by stitching multiple traces. The error motions are optimally recognized and then removed from the trace measurement based on the least squares principle. We model the objective function by relating the normal error to the rigid body transformation of each trace. The basic idea is to minimize the inconsistency of all intersection points of different traces simultaneously. Finally the algorithm is verified through simulations. It shows that error motions of sub-milliradian scale are even tolerant with the surface reconstruction algorithm.

1. Introduction

Optical surfaces are usually not specular during the grinding and lapping stage before they are polished to higher precision and higher surface quality. Interferometry is thus not applicable and coordinate measuring machines (CMMs) are typical solutions. However, uncertainty of CMMs increases severely with the size of the test surface. For several meter-class surfaces, it is difficult and expensive to achieve surface measuring accuracy higher than 10 μm with a CMM. How to bridge the gap between the CMM and the interferometer is still a challenge.

Swing arm profilometry is expected of high precision for measuring large surfaces. Without large stroke linear axes, it takes full advantage of ultra-precision rotary bearings and high precision probes. The basic principle is schematically shown in Fig. 1 for measuring a concave surface. The probe is mounted at the end of a swing arm which is rotated by the swing rotary table. The swing rotary axis is inclined and intersects with the optical axis of the test surface at point C. The angle of these two axes is denoted by θ. Initially the probe is aligned perpendicular to the test surface at the vertex. As the swing arm rotates, the probe travels across the surface with an arc trace lying on the reference sphere whose center is point C and radius of curvature is r. The readout of the probe is hence the deviation of the test surface from the reference sphere. If we choose the best-fit sphere of aspheres for the reference by setting proper angle θ and swing arm length, the range of the probe readout is minimized. Therefore we can use high precision probes with small range of measurement. The test surface is also azimuthally indexed by the part rotary table so as to be probed trace by trace. Multiple traces cross each other and are finally processed to give the surface error.

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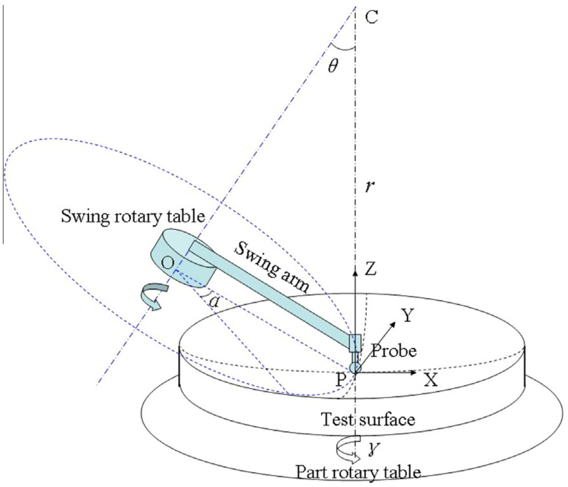

Fig. 1. Schematic diagram of swing arm profilometry for concave surfaces.

The swing arm profilometer acts like a two-dimensional version of spherical interferometer. It generates the arc trace on the reference sphere by utilizing ultra-precision rotary bearings. And the range of measurement of probes is usually much larger than the dynamic range of the interferometer. Another advantage of swing arm profilometer is that it facilitates in-situ test of large aspheres on the lapping machine.

The first swing arm profilometer was developed at the University of Arizona. Anderson and Burge analyzed some error source of swing arm profilometry qualitatively and gave simulation results of sensitivity to some errors for the measurement of the *f*/4 LBT secondary [1]. Su et al. realized that the odd component of the surface error can be canceled out by averaging all the scan data and the residual odd component is calibrated as systematic error. The even systematic error is calibrated by full aperture interferometric test. The systematic error includes contributions of both the swing rotary table and the part rotary table, and even misalignment. They then proposed the maximum likelihood reconstruction method to stitch the scans into a surface in virtue of crossing of different scans [2]. Recently a dual probe self-calibration mode was proposed to separate the swing arm bearing error except some harmonic components. The two probes need to be accurately positioned to detect the same trace [3].

Jing et al. proposed a swing arm profilometer quite different from the original one for measuring telescope mirror-segments [4]. Concentric circular traces are scanned at different radial position. During each scan, the probe is held stationary while the test surface is rotated. No crossing exists between the traces and the error of the rotary table is assumed repeatable. It is calibrated by probing a circular trace on a spherical artifact which can also be measured by an interferometer. Difference from interferometric result gives the error of the rotary table which is used to predict the error at other radial position proportionally. A dual-probe method was also presented to calibrate the error motions of the part rotary table by scanning two probes arranged coplanar with the axis of the swing rotary table [5]. The two probes detect the surface height change at different polar radius on the artifact plane. This kind of method requires that the error is highly repeatable and axial runout is negligible. Error motions of a rotary table include not only tilt, but also axial and radial runout [6]. According to ANSI standard ASME B89.3.4-2010, error motions of rotary stages are composed of synchronous part and asynchronous part. The former repeats each revolution while the asynchronous part does not repeat. For the part rotary table, even the synchronous error motion is not strictly repeatable as it is influenced by different load. Another version of swing arm profilometer was proposed for measurement of influence function by setting the swing arm bearing axis parallel to the part rotation axis [7]. Measurement uncertainty is analyzed but the error motion of both the part rotary table and the swing arm bearing is simply the radial runout while tilt may be a significant error source.

Besides the error motions of the rotary tables, misalignment of the system also contributes to the measurement error which is typically of low spatial frequency. The misalignment includes deviation of the axes of two rotary tables and decentering of the probe from the axis of the part rotary table. Expensive apparatuses and time-consuming procedures are currently required to align the swing arm profilometer. For instance, Su et al. employed a laser tracker in combination of a point source microscope to position the probe tip precisely [3]. The length of swing arm can be determined with accurate distance measurement by four laser trackers utilizing multilateration [8]. Chen et al. also proposed to use a spectral confocal sensor to calibrate the decentering of the probe tip [9].

Aiming to develop a prototype swing arm profilometer for several meter-class aspheres with micron accuracy, we first present quantitative error analysis for tolerancing the optomechanical design. The error sources include axial, radial and tilt motions of the swing rotary table and the part rotary table as well as misalignment of the axes of the two rotary tables. A surface reconstruction algorithm is then proposed to separate the error motions of the part rotary table by stitching multiple traces with the inconsistency of all intersection points of different traces simultaneously minimized.

2. Coordinate transformation of swing arm profilometry

The Cartesian frame is built at the vertex P of the reference sphere and Z axis is the optical axis. Initially the probe tip coincides with the vertex. The inclined axis of swing rotary table lies on $-X$ axis. As the swing arm rotates, the coordinates (x,y,z) of the probe tip on the arc trace are given as below by rigid body transformations:

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = R_y T_x R_z \begin{bmatrix} r\sin\theta \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} r\cos\theta\sin\theta(\cos\alpha - 1) \\ r\sin\alpha\sin\theta \\ r\sin^2\theta(1-\cos\alpha) \\ 1 \end{bmatrix} \tag{1}$$