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NDT&E International 38 (2005) 442–447

NDT&E international

www.elsevier.com/locate/ndteint

Novel 3D sphericity evaluation based on SFS-NDT

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Received 8 November 2004; accepted 28 December 2004
Available online 11 February 2005

Abstract

Sphericity evaluation is an important work in modern industry. Because the former 3D measurement is complex and with low precision, a lot of sphericity evaluation is studied only based on 2D measurement. But the 2D sphericity evaluation method is reported unreasonable because sphere is a 3D object. In order to evaluate sphericity error accurately and effectively, based on SFS-NDT 3D measurement method studied in reference [Research on 3D recovery based on only one online measuring image. TianJin University, Doctor thesis (2004)], this paper proposes a novel 3D sphericity evaluation method, which use all the 3D data in the evaluation procedure. Minimum zone solution using all the 3D data is adopted to make the evaluation more accurate and reliable. Compared with the conventional sphericity evaluation based on 2D measurement, the proposed 3D evaluation has the merits of non-contact, non-destructive, low cost, high speed, and high reliable. 3D shape recovery of a sphere based on SFS and its 3D sphericity evaluation procedure will be analyzed in this paper.

Keywords: SFS; 3D sphericity evaluation; Minimum zone

1. Introduction

Spherical form (sphericity) error has a considerable effect on rotating motion in many machines. Any defects such as surface roughness, waviness and form error on a spherical surface may result in the generation of a large amount of heat and in turn lead to wear and life reduction. Therefore, it is very important to evaluate sphericity error accurately and effectively.

In the ISO (3290) [1], deviation from sphericity is measured in two or three equatorial planes at 90° to each other. The value of the sphericity is calculated using the minimum circumscribing circle method applied to the two or three profiles. All these profiles are mostly plotted by a contact circularity instrument, which is shown in Fig. 1. It is reported that a considerable difference exists between 2D and 3D evaluations of surface roughness [2]. This means that the determination of sphericity using 2D measurements is unreasonable. However, the former 3D measurement technology is complex and with low precision, so the ISO (1101) [3] does not deal with sphericity tolerance explicitly. Therefore, based on the concepts of 2D measurement of circularity and cylindricity tolerances dealt with in ISO (1101), the 2D sphericity error based on the minimum zone solution is formulated. And from the beginning research of minimum zone solution, some efforts have been devoted to evaluating the sphericity error using different minimum algorithm.

(1) Using discrete Chebyshev approximations, Danish [4] calculated the minimum zone solution for sphericity error;
(2) Kanada [5] computed the minimum zone sphericity using iterative least squares and the downhill simplex search methods;
(3) Fan and Lee [6] proposed an approach with minimum potential energy analogy to the minimum zone solution of spherical form error. And the problem of finding the minimum zone sphericity error is transformed into that of finding the minimum elastic potential energy of the corresponding mechanical system;

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doi:10.1016/j.ndteint.2004.12.005

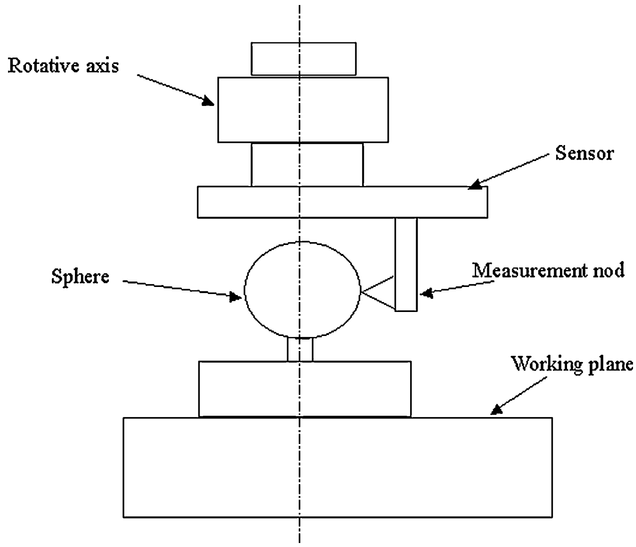

Fig. 1. Sketch of 'circularity instrument'.

(4) Chen [7] constructed three mathematical models to evaluate the minimum circumscribed sphere, the maximum inscribed sphere and the minimum zone sphere by directly resolving the simultaneous linear algebraic equations first. Then, the minimum zone solutions can be obtained by comparing the solutions between the 4–1 models, the 1–4 models, the 3–2 models and the 2–3 models;
(5) Samuel [8] established the minimum circumscribed limacoid, maximum inscribed limacoid and minimum zone limacoid based on the computational geometry to evaluate sphericity error.
(6) With the emergence of computational intelligence, intelligence-oriented algorithms such as genetic algorithms (GAs) have been employed to evaluate form errors such as flatness, straightness, cylindricity, sphericity, [9] etc. Genetic algorithms based on the principles of population evolution have been theoretically and empirically proven to be robust for searching for solutions in complex spaces, and by using GAs the form errors will be evolved toward the optimal solution.
(7) Wen [10] using immune algorithm (IA) for sphericity error evaluation. It is proven that IA is a favorable alternative for solving minimum zone sphericity error.

All the above sphericity evaluation method is based on 2D measurement data. It is unreasonable because sphere is a 3D object. So sphericity evaluation based on 3D measurement is needed to be researched. In the doctor thesis—'Research on 3D recovery based on only one online measuring image' [11], novel non-contact 3D measurement method-SFS is introduced. SFS is a visual inspection method, but different compared with other vision techniques because it can visualize the 3D-data of an object by measuring only one image. This image is captured by a CCD or other type of camera. The merits of SFS are easy operating, non-contact, non-destructive, low cost, high speed, and high precision. If a sphere is placed under a CCD that is in good measurement status, then the 3D data of the sphere can be recovered by SFS.

It is the purpose of this paper to propose a novel 3D sphericity evaluation method. The proposed evaluation method is based on SFS technique. Compared with 2D sphericity evaluation method, the proposed evaluation method is not using only two or three equatorial planes of a sphere to judge sphericity error, but using all the 3D data of the recovered sphere. The paper is organized as follows: 3D shape recovery of a sphere based on SFS; then 3D sphericity error evaluation method is proposed; the last is conclusion.

2. 3D shape recovery of a sphere based on SFS

In computer vision, the techniques to recover shape are called shape-from-X techniques, where X can be shading, stereo, motion, and texture. SFS deals with the recovery of shape from a gradual variation of shading in the image. To solve SFS problem, it is important to study how the images are formed. A simple model of image formation is the Lambertian model, in which the gray level at a pixel in the image depends on the light source direction and the surface normal. In SFS, given a gray level image, the aim is to recover the light source and the surface shape at each pixel in the image. However, real images do not always follow the Lambertian model, Even if we assume Lambertian reflectance. Therefore, it is difficult to find a unique solution to SFS; it requires additional constraints. In the doctor thesis [11], a good solution for SFS is introduced. This proposed SFS in [11] is to find the slant Φ and tilt θ of each pixel in the image. According to the relationship between slant-tilt and surface normal, the true depth of each pixel can be calculated.

Assume that the energy of the incident light is $I(x, y)$, the vector of the light source direction is (Φ_s, θ_s), the gray of each pixel in the image is E_i, the maximum gray in the image is E_{max}. Then the slant and tilt of each pixel can be got by formula (1) and (2).

$$\phi_i = \arccos \frac{E_i}{E_{max}} \tag{1}$$

$$\theta_i = \arctan \frac{I_y \cos\theta_s - I_x \sin\theta_s}{I_x \cos\theta_s \cos\phi_s + I_y \cos\phi_s \sin\theta_s} \tag{2}$$

Assume that the normal of each point in the object is (n_{ix}, n_{iy}, n_{iz}), and then the normal can be got from Φ_i and θ_i by formula (3).

$$n_x = \sin\phi_i \cos\theta_i,\ n_y = \sin\phi_i \sin\theta_i,\ n_z = \cos\phi_i \tag{3}$$

When the entire surface normal is got, the shape of the recovered object can be plotted. In our experiment,