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Method for sphericity error evaluation using geometry optimization searching algorithm

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ABSTRACT

According to geometrical characteristics of the sphericity error, a new evaluation algorithm for sphericity error based on geometry optimization searching method has been presented. First, the reference point is established and the initial error is calculated by using the measured points, Second, a regular hexahedron of side length *f* is collocated by taking the reference point as datum point, and the maximum difference of the radius of all measured points are calculated by regarding each vertex of the hexahedron as the centre of the measured spherical surface. Third, the reference point or side length of the hexahedron is changed by comparing the initial error and the maximum difference of the radius. Step by step, the sphericity error value of corresponding evaluation method (including Minimum Zone Sphere method (MZS), Minimum Circumscribed Sphere method (MCS) and Maximum Inscribed Sphere method (MIS)) are obtained. The principle and the steps of using the algorithm to solve the sphericity error are described in detail and the mathematical formula and program flowchart are given. The experimental results show that the sphericity error can be evaluated effectively and exactly with this algorithm.

1. Introduction

Sphericity error is the variation of the actual measured spherical surface to its ideal spherical surface, and the error value is equal to the radius difference of the two concentric spheres containing all measured points. The size of sphericity error has a great influence on rotation accuracy of the machinery products; therefore, it is very important to study the sphericity error evaluating algorithm

Comparing with the evaluation of straightness error, flatness error and roundness error, the evaluation of sphericity error is much more difficult and complex. The usual methods of evaluating sphericity error include Least Square Sphere method (LSS), Minimum Zone Sphere method (MZS), Minimum Circumscribed Sphere method (MCS) and Maximum Inscribed Sphere method (MIC). The LSS method is used to minimize the sum of square errors for part profile evaluation and the error value is unique. Because the LSS method is simple and is to implement, it is now widely used. But the LSS method is in breach of the minimum conditions definition of form error evaluation and therefore the sphericity error value calculated by the LSS method is not minimal.

The MZS method is the error evaluation method for sphericity in line with the ISO definition. The key technology of the MZS method is to search two homocentric sphere surfaces containing all measured points, and the radius difference of the two homocentric sphere surfaces is minimum. In the MZS method, complexity data of processing algorithm is critical, so many approximative and relative accuracy methods, such as MCS method and MIS method, had been established. The objective functions of the MZS, MIS and MCS evaluation method for sphericity error are non-linear and many parameters need to be optimized, so far at least, the accurate assessment problem has not been formally solved.

To improve evaluation accuracy of sphericity error, many scholars have launched research on the sphericity error evaluation algorithm. Using discrete Chebyshev approximations, Danish and Shunmugam [1] calculated the minimum zone solution for sphericity error. Kanada [2] computed the minimum zone sphericity using iterative least squares and the downhill simplex search methods. Cui et al. [3] established the mathematical model of sphericity error based on the mathematical definition of the minimum zone method, through the critical conditions such as: the initial value of the choice, the determinant factor of the genetic operators and so on, proposed a novel sphericity error evaluation method based on genetic algorithm. Soman et al. [4] thought with the availability of high speed inspection machines and the ability to generate large datasets with minimal effort and time, the evaluation algorithm

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becomes a critical component of the inspection time and proposed an approach for evaluation of minimum zone sphericity tolerance using a selective zone search method. Fan and Lee [5] 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. Chen and Liu [6] 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 model, the 1-4 model, the 3-2 model and the 2-3 model. Samuel and Shunmugam [7] thought the sphericity error is evaluated with reference to an assessment feature, referred to as a limacoid, and established the minimum circumscribed limacoid, maximum inscribed limacoid and minimum zone limacoid based on the computational geometry to evaluate sphericity error. Wen and Song [8,9] defined the concepts of the minimum zone sphere (MZS), the minimum circumscribed sphere (MCS) and the maximum inscribed sphere (MIS), and formulated their objective function calculation methods. And then they proposed an improved genetic algorithm and an immune evolutionary algorithm (IEA) by imitating the defense process of the immune system and the ideas of mutation in evolutionary biology for sphericity error evaluation. He et al. [10] proposed the mathematical modeling for evaluation of the sphericity error with minimum radial separation centre and devised a geometric approximation technique. The technique regarded the least square sphere centre as the initial centre of the concentric spheres containing all measured points, and then the centre was moved gradually to reduce the radial separation till the minimum radial separation centre was obtained where the constructed concentric spheres conformed to the minimum zone condition. Experiment shows that the obtained sphericity error is smaller than the least square solution. Meng et al. [11–13] thought the evaluation of sphericity error is formulated as a non-differentiable unconstrained optimization problem and hard to handle. The minimum circumscribed sphere and the maximum inscribed sphere are all easily solved by iterative comparisons, so the relationship between the minimum zone sphere, the minimum circumscribed sphere and the maximum inscribed sphere is proposed to efficiently solve the minimum zone problem. And they presented sphericity evaluation method of MCC and MIC based on the convex hull and concave theory respectively. Liu and Peng [14] established a 3D model of measuring and computing based on Cartesian coordinates, based on the geometric curved surface character of circumscribed sphere analysis and research, constructed the evaluation method of “2 + 1”,“3 + 1”,“4 + 1” for MCS. Peng et al. [15] raised sphericity error evaluation mathematical model based on minimum area method and standard uncertainty specific calculating method through studying each element’s trans-mission coefficient and correlation coefficient which affect standard uncertainty. The sphericity error value is obtained by using improved particle swarm optimization (PSO) algorithm.

From the references it can be seen that the core issue of the evaluation of sphericity error is to find the sphere centre of the two concentric sphere surfaces containing all measured points, such that the radius difference of the two homocentric sphere surfaces is minimum. The construction of the minimum zone is a complex geometric problem, which can be formulated as a nonlinear optimization, in particular the MZS, which are nonlinear constrained optimization problems. Meanwhile, convergence rate, precision of result and reliability of the error evaluation algorithm directly affect the evaluating precision of sphericity error. So, the research of simple and practical algorithm for the sphericity error evaluation is badly needed.

According to the definition and the geometrical characteristics of the sphericity error, an innovative and simple sphericity error evaluation method, named as Geometric Optimization Searching Algorithm (GOSA) is presented, in which the sphericity error can be gained by calling distance functions between point to point and judging and changing the reference point repeatedly. The sphericity error of the MZS, MCS and MIS method could be achieved more accurately and effectively.

2. The principle of the GOSA

The core of sphericity evaluation methods (LSS, MIS, MCS and MZS) is to resolve the parameters of the centre of the two concentric sphere surfaces containing all measured points [1–13]. Upon this, the principle of the GOSA is as follows.

First, the reference point is established by using step 3.1, and a regular hexahedron of side length f is collocated by taking the reference point as datum point (For methods of determining value of side length f, see step 3.2), then coordinate values of the 8 auxiliary points (that is, the 8 vertices of the hexahedron) are determined.

According to the definition of the sphericity error, we can know that, after the confirmation of the centre coordinates, the radial extreme difference of all measured points is the sphericity error. So, with the reference point as the centre of the measured sphere surface, the sphericity error can be obtained. For convenience, this error is expressed by A. Similar, taking the 8 auxiliary points as assumed ideal centre of measured sphere surface respectively, by calculating the radii of all measured points, the 8 radial extreme differences (that is, the 8 sphericity error) are also gained.

If the minimum of the 8 sphericity error is less than the A, the reference point changes to the auxiliary point corresponding to the minimum of the radius difference, the length of side is also f, a new regular hexahedron is re-established. Thus the 8 new auxiliary points as well as the 8 new sphericity error can be gained. And this process is repeated.

If the minimum of the 8 sphericity error is not less than the A, the new hexahedron is re-established by using the 0.618f as the side length and the reference point remain unchanged. Thus the 8 new auxiliary points as well as the 8 new sphericity error can be gained. And this process is repeated.

When the side length of the hexahedron is less than the preset value δ (normally, $\delta = 0.00001$ mm), it could be considered that the searched assumption centre is getting close to the ideal centre of the two concentric sphere surfaces which is the minimum radius difference and contains all the measured points, the search terminates.

3. The process and steps of the GOSA

Assuming that the measured points are expressed by $P_j(x_j, y_j, z_j)$ $(j = 1, 2, \ldots, N)$

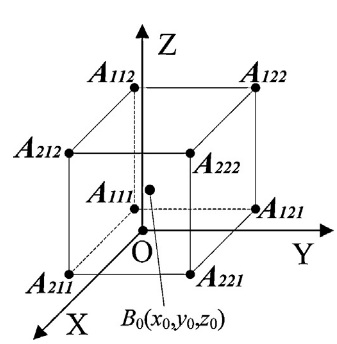

Fig. 1. The relationship between the auxiliary points and the reference point.