Evaluation method of minimum area roundness error based on sector search

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Abstract. The evaluation of roundness error has an important reference in the quality evaluation of shaft parts. Aiming at the problems of principle error, model error and non-linear solution difficulty in the existing roundness error evaluation algorithm, the area search algorithm is combined with the roundness error minimum inclusive area evaluation method, and the area fan search method is used. The error is evaluated. By constructing reasonable simulation data and using the designed evaluation method to calculate the roundness error of the simulation data, the results of the roundness error of different evaluation methods are compared and analyzed. And the actual roundness error evaluation and method verification are carried out through experiments. The results show that this method is simple to operate, stable and reliable, and has higher calculation efficiency, and the evaluation accuracy is significantly improved compared with the least square method, the largest inscribed circle method, and the smallest circumscribed circle method.

1. Introduction

Currently, there are four widely used roundness error evaluation methods. They are the least square method, the smallest contained area method, the smallest circumscribed circle method and the largest inscribed circle method[1]. Among them, because the least squares method linearizes the nonlinear problem through approximation and is easy to operate, it is widely used, and some European and American countries list it as a national standard[2-4]. However, because the least squares method is a nonlinear solution problem, it is difficult to solve, and there are many specific requirements for the sampling data in the linearization process, which adds a lot of inconvenience to the actual measurement process, and the least squares method does not meet the roundness error evaluation criterion The minimum condition of the radius difference in[5-6]. Among them, the minimum circumscribed circle method is suitable for the evaluation of the roundness error of the outer surface of shaft parts, and the maximum inscribed circle method is suitable for the evaluation of the roundness error of the inner surface of the hole type parts. However, these two evaluation methods do not meet the definition of roundness error in international standards. The minimum area method is the only evaluation method that meets the international standard definition of roundness error among the above four methods[7]. However, this method is a nonlinear optimization problem, which is not easy to solve directly, so it is necessary to study the roundness error evaluation algorithm from different angles[8-9].

Aiming at the problems in the above evaluation methods, a roundness error evaluation method that combines the area search algorithm and the minimum containment area method is proposed.


principle of the evaluation method is simple and clear, the method is easy to operate and feasible, conforms to the definition of roundness error in international standards, and the calculation process has good stability and the calculation speed is faster.

2. The principle of the roundness error evaluation method of the smallest area based on sector search
Aiming at the above-mentioned roundness error evaluation problem, a method for evaluating the roundness error of the smallest area based on sector search is proposed. First, apply the least square method to circle the data points to obtain the least square center O (A, B), and use the center as the center of the minimum area method to obtain the roundness error f of the least square method. The three data points C1, C2, C3 with the largest distance from the center O are screened out, and the center O1 (A1, B1) of the circle determined by the three data points is calculated. In the same way, the three data points D1, D2, D3 with the smallest distance from the circle center O are selected, and the circle center O2 (A2, B2) of the circle determined by the three data points is calculated. Determine the triangle area with O, O1, O2, three points, as the search area of the center of the minimum area method. Take the circle center O as the starting point, triangle sides O, O1 as the starting edges, f/k (k value can be set according to the accuracy requirements) as the length increment, and θ/(n*N) (θ=∠O1OO2, N is the number of data points, the value of n can be set according to the accuracy requirements) is the angle increment, constructs a fan-shaped grid, performs area search, and uses each grid point as the center of the circle, and calculates its roundness error according to the minimum contained area method, And numerically compare the roundness error values calculated from all grid points. The minimum value is the roundness error of the minimum contained area method, and the corresponding grid point is the center of the minimum contained area method. As shown in Figure 1.

![Figure1. The construction of grid search points in area.](image)

3. Steps of the minimum area roundness error evaluation method based on sector search
(1) Use the least square method to fit the sampling data P(xi,yi) of the actual circle contour, where i=1,2,...,N. And calculate the least squares circle center O (A, B), and the least squares roundness error f. Calculated as follows:

\[
A = -E / 2; \\
B = -F / 2; \\
E = (H^T H)^{-1} Y; \\
F = (H^T H)^{-1} H^T I; \\
G
\]

(1)
Calculate the distance \( L_i \) from each data point \( P_i \) to the center \( O \), and filter out the three points \( C_1(x_{c1}, y_{c1}), C_2(x_{c2}, y_{c2}), C_3(x_{c3}, y_{c3}) \), and the distance value with the largest distance value \( \text{The smallest three points } D_1(x_{d1}, y_{d1}), D_2(x_{d2}, y_{d2}), D_3(x_{d3}, y_{d3}) \). Methods as below:

(3) Calculate \( C_1(x_{c1}, y_{c1}), C_2(x_{c2}, y_{c2}), C_3(x_{c3}, y_{c3}) \), the center of the circle determined by the three points \( O_1(A_1, B_1) \). And calculate \( D_1(x_{d1}, y_{d1}), D_2(x_{d2}, y_{d2}), D_3(x_{d3}, y_{d3}) \), the center of the circle determined by the three points \( O_2(A_2, B_2) \).

(4) Draw a triangular area with three points \( O, O_1, O_2 \) as vertices, and use this area as the search area.

(5) Take the circle center \( O \) as the starting point, the triangle sides \( O \) and \( O_1 \) as the starting sides, and \( \text{flc=flc}/(k \text{ value can be set according to the accuracy requirements}) \) as the length increment, \( \theta_{lc}=\theta/(n*N) \) \( (\theta \text{ is } \angle O_1OO_2, N \text{ is the number of data points, and the value of } n \text{ can be set according to the accuracy requirements}) \) is the angle increment to construct a fan-shaped grid. Then the coordinates of the grid point \( Q_{ij}(x_{ij}, y_{ij}) \) are

\[
x_{ij}=A+j*\text{flc} \cos(\Theta+i*\Theta_{lc}); \\
y_{ij}=B+j*\text{flc} \sin(\Theta+i*\Theta_{lc});
\]  

(6) With each grid point as the center of the circle, calculate the radius value of all corresponding grid points, and find the maximum radius value \( R_{\text{max}} \) and the minimum radius value \( R_{\text{min}} \) at this time, then the extreme value difference of the radius at this time is \( R_{\text{mm}}=R_{\text{max}}-R_{\text{min}} \).

(7) Compare all the radius range values \( R_{\text{mm}} \), where the grid point that satisfies the minimum \( R_{\text{mm}} \) is the accurate minimum area circle center, and the radius range difference at this time is the minimum contained circle roundness error. Based on sector search is shown in Figure 2.
Figure 2. Flow chart of the algorithm for evaluating the minimum area roundness error based on sector search.

4. Experimental verification
(1) Place a shaft-type part with a diameter of 21.8mm on the shaft-type part measuring table, and adjust its axis to be coaxial with the rotation axis of the measuring platform. Record the radius value of each point of the fixed interface of the shaft part in the process of one revolution.

(2) Convert polar coordinate data to direct coordinate system data, the formula is as follows.

\[ x = \rho \cos(\theta); \quad (9) \]
\[ y = \rho \sin(\theta). \quad (10) \]

Data processing. Several commonly used roundness error evaluation methods and the methods proposed in this article are used to process the actual measured sampling point data. Import the measurement data into the evaluation algorithm program to calculate the results of the four evaluation methods and their center coordinates. For the evaluation method in this article, set the search length increment to \( \frac{\text{flc}}{1000} \) and the angle increment to \( \frac{\theta}{(2*N)} \). The results are shown in Table 1.
### Table 1. Experimental data processing results.

| Method                | Center abscissa (x/mm) | Center ordinate (y/mm) | Roundness error (mm) |
|-----------------------|------------------------|------------------------|----------------------|
| Least squares         | 0                      | -0.0011                | 0.0046               |
| Maximum inscribed     | 0.0522                 | 0.0051                 | 0.1085               |
| Minimum circumscribed | -0.0579                | 0.0128                 | 0.1190               |
| Minimum area method   | -0.0564                | 0.0125                 | 0.0044               |

(4) Analysis of experimental results.
From the comparison of the roundness error results of the four evaluation methods in the table, it can be found that the roundness error evaluation method proposed in this paper is more accurate. Compared with the maximum inscribed circle method, its accuracy is relatively improved by 95.94%. Relative to the smallest circumscribed circle method, the accuracy is 96.30%. Compared with the least square method, its accuracy is relatively improved by 4.55%. Through the comparison of the data in the table, the roundness error evaluation method using the triangular area sector search algorithm has smaller errors, and the roundness error results obtained have higher accuracy. In addition, the results can be obtained when the program is run once in order, indicating that the evaluation method has fewer iterations and higher efficiency.

5. Conclusion
(1) The roundness error evaluation method of the smallest area based on the sector search, the least squares center, radius and roundness errors are calculated by the least square method, and the center of the largest inscribed circle method and the largest circumscribed circle method are obtained by circle fitting. Determine the triangle search area, and then set the search length increment and angle increment according to the least squares roundness error and the angle of the triangle area to realize the accurate calculation of the roundness error.

(2) The roundness error evaluation method of the minimum area based on the sector search, the roundness error result of the minimum area method can be calculated by running the program only once, and the accurate processing of the roundness error polar coordinate measurement data and rectangular coordinate measurement data can be realized.

(3) The roundness error evaluation method of the smallest area based on sector search provides a new idea for roundness error evaluation. The principle is clear and feasible, there is no special requirement for sampling data, and the adaptability is strong. The algorithm overcomes the minimum nonlinear problem of the square method is difficult to solve, and the reliable center of the minimum containment area can be found, and the roundness error calculated has higher accuracy. Simulation and experimental results show that the evaluation method has good stability for each set of data.

(4) The accuracy of the evaluation method is affected by the two parameters of angle increment and length increment in the area search process, and higher area search accuracy can be obtained by adjusting the values of these two parameters. However, while increasing the number of grid points to improve the calculation accuracy, it will increase the amount of calculation and affect the calculation speed. Therefore, in practical applications, these two parameters can be adjusted according to the number of sample data, so that the accuracy and the amount of calculation can meet the requirements. At the same time, the author also evaluated the data in other literatures about roundness error evaluation methods, and the results are consistent with the results obtained in the literature, and have a faster running speed.
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