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Intersecting chord method for minimum zone evaluation of roundness deviation using Cartesian coordinate data

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ABSTRACT

Minimum zone evaluation of roundness deviation is a very important and complex problem in precision measurement. Along with the continuous development of precision machining technology, it has become an increasingly prominent issue of how to quickly and accurately evaluate the minimum zone roundness deviation from a large number of coordinate data. In this paper, an intersecting chord method is first proposed to realize the minimum zone model of roundness deviation with coordinate data. The new modelling method uses the crossing relationship of chords to construct the intersecting structure and the 2 + 2 evaluation model of the minimum zone roundness deviation, which can not only accurately determine the position of minimum zone centre but also greatly improve the computational efficiency of modelling process. Using the related chords and their extreme points to generate a virtual centre, this may reduce the deviation between the intersecting chords structure and the centre of the minimum zone evaluation. The proposed method makes use of the geometric relationship of chords, so the minimum zone roundness deviation can be obtained without the optimal method or the point-by-point method. The validation test of the proposed method is designed to analyze a coordinate dataset published in other literature. Comparing the proposed method with the published method, it is easy to show that the relative error between two results is less than 0.4%. Finally, an experiment is also given to indicate that the calculation accuracy and the evaluation efficiency of the proposed method achieve a satisfactory conclusion.

1. Introduction

Roundness deviation is an important component of geometric tolerance which plays a key role in manufacture and measurement. In machining, cylindrical surfaces are ubiquitous and the realization of high-quality cylinders is a crucial technical objective [1]. The accurate evaluation of the roundness deviation can reduce the risk that defective cylindrical parts are accepted as good products. At present, coordinate measuring machine (CMM) used as a typical measuring instrument in Cartesian coordinates is widely used in industrial measurement and metrology fields. Therefore, the development of a high accuracy and efficiency analytical method of the roundness deviation becomes an indispensible requirement. So, extensive researches in the area of roundness measurement and evaluation are still being carried out [1–23].

With the help of the mathematical model, the roundness deviation is defined as the difference between the radius of circumcircle and that of incircle, the definition was also given in ASME and ISO standards [2–5]. Normally, the roundness deviation has four kinds of typical evaluation techniques: least square circle (LSCI), minimum circumscribed circle (MCCI), maximum inscribed circle (MICI), and minimum zone circle (MZCI). The LSCI is the most commonly used evaluation technique of the roundness deviation based on the statistical regression analysis, which can minimize the sum of the square residuals of the errors made in the data fitting. In the practical application, the LSCI is mainly used to deal with the simple solution and the uniqueness of its solution in error evaluation. Differing from the LSCI, the MZCI is considered to be an evaluation criterion of the roundness deviation in accordance with the minimum condition principles. However, this technique is subject to certain limitations from a complex modelling process, and it has not yet formed a best solution up till now. That is why, it

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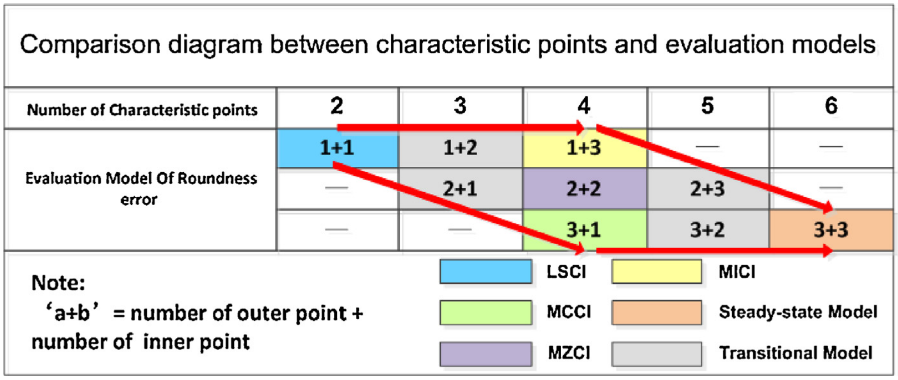

Fig. 1. Relationship between the number of characteristic points and the evaluation models of the roundness deviation.

has attracted more interests of researcher to develop an effective modelling method for the MZCI evaluation.

There are some research studies of the MZCI evaluation proposed in the past years. Chen [6] developed a vision-based inspection system for roundness measurements, and a stochastic optimization approach has been proposed to compute the reference circles of the MZCI. Rossi [8] introduced an optimal blind sampling strategy for minimum zone roundness evaluation by metaheuristics. Li [14] proposed a determinant condition of the minimum zone circle, where the minimum zone lines determined by four critical measured points can be constructed with convex hull and coordinates transmission. Finaly, the rapid selection of iteration points with convex hull leads an efficient way to solve the minimax solution. Du [16] elaborated the standard PSO algorithm and theory analysis about the impact of value selection of some important parameters for the roundness deviation evaluation based on minimum zone circle. The above research studies reviewed have different solutions to the minimum zone circle evaluation, however, they mainly focus on the requirement that the optimization techniques is used to deal with the nonlinear problem of the MZCI. Although various optimization techniques can promote the growth of the MZCI technique, the result of the MZCI can be obtained through optimizing the measured object or seeking the optimal value. But, as a complex space geometry problem, the model of the MZCI has to be further studied using appropriate approaches to accurately evaluate the roundness deviation.

In this paper, the mathematical description based on the intersecting chords (IC) is proposed to implement the MZCI evaluation of the roundness deviation. Essentially, from a control point to a global chord, the intersecting chord method is gradually applied to reduce the number of iterations and improve the efficiency of evaluation, and then several experiments are carried out using Cartesian coordinate data to verify the effectiveness of the proposed method.

2. Basic theory and description of minimum zone circle

2.1. Relationship among the LSCI, MICI, MCCI and MZCI

According to the spatial structures and the geometric relationship of the roundness deviation models, the whole profile of measurement section must be modelled by control points to fully describe the characteristics of the roundness model. The roundness deviation model is defined as the form of '$N+M$', that is, N points on the outer circle and M points on the inner circle. The outer and inner circles are two concentric circles, and all of the sampling points lie in the space between the two circles. As can be seen in Fig. 1, the LSCI is considered as a 1 + 1 model, the MCCI is considered as a combination of the 2 + 1 and 3 + 1 models, the MICI method is considered as a combination of the 1 + 2 and 1 + 3 models, and the MZCI method is considered as the 2 + 2 model, respectively. In the above four evaluation methods, the MZCI is an optimal evaluation method, which has the minimum error and the two concentric circles enclosing all data points. As a result, the MZCI is considered as the best judgment criterion for the evaluation of the roundness deviation.

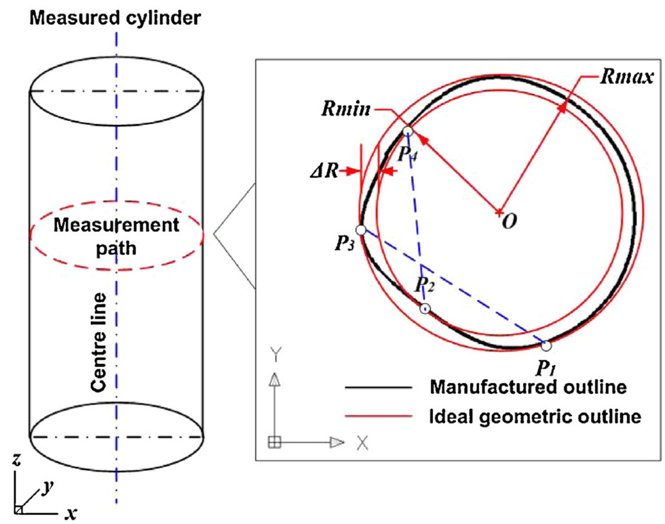

Fig. 2. ΔR is the difference between the radius of the two circles and is the roundness deviation. R_{max} and R_{min} are radius of the two concentric circles, respectively. O is the locations of the centre of a circle. P_1 and P_3 are the outside contact points of the outer circle. P_2 and P_4 are the inside contact points of the inner circle. Chords P_1P_2 and P_3P_4 have a spatial crossing structure.

2.2. Definition of minimum zone circle

Generally, the actual object usually deviate from the specified ideal geometry in the processing procedure, the deviation produced is considered to be form error. The roundness deviation is one of the main types of form error and is defined as the difference between the radius of circumscircle and that of incircle (as shown in Fig. 2), that is, the roundness deviation can be defined as

$$\Delta R = \left|R_{\max}\right| - \left|R_{\min}\right|,$$

where ΔR is the value of the roundness deviation, R_{max} is the radius of outer circle, and R_{min} is the radius of inner circle.

For the MZCI, two concentric circles are used as the reference basis for measuring the roundness deviation. The outer circle is located outside the roundness profile just as to surround the whole roundness profile and the inner circle is located inside the roundness profile so that it just inscribes the roundness profile. According to the definition of characteristic point model, the number of