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Batch circular form error characterization and evaluation

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ABSTRACT

In practice, it is necessary to understand the general quality status of a batch of circular features machined under the same or similar conditions. In particular, it is necessary to understand the possible worst case among such a batch of circular features. To this end, a brand-new concept called “batch circular form error” is presented in this paper. Detailed definitions of batch circular form error including batch circular form error with ideal conditions and batch circular form error with realistic conditions are provided. Accordingly, the evaluation algorithms of batch circular form error are developed. The algorithms include the characterization of the deterministic profile of circular features and the evaluation of batch circular form error based on a given profile confidence level. Case studies with simulation and experimental data are used for demonstration. The results show that the batch circular form error can be estimated with the data measured from any circular feature in the batch, as long as the sample size is large enough and random ratio is not too large.

1. Introduction

According to ANSI standards (ANSI 14.5M), the circular form error is the gap between two concentric circles that just bound completely the entire circular feature. However, this standard does not give any guidelines to establish this region. Hence, many algorithms have been developed for circular form error evaluation [1–4]. Among these algorithms, minimum zone fitting and least squares fitting are two basic adopted approaches. Researches show that least squares fitting cannot give a minimum circular form error value with available data [5,6]. And minimum zone fitting is very conformable to the tolerance definition on ANSI standards. This results in most algorithms that focused on investigating how to obtain the minimum circular form error value with available data. For example, many researchers addressed how to solve a general optimization problem to get the circular form error value [2,7–14]. However, for an optimization problem, it is not easy to obtain the global minimum value. To get a value that is close to the global minimum one, some researchers addressed the initial conditions and adopted coordinate transformation techniques [12,13] or suggested approximating orthogonal residuals by functions that are linear in the feature parameters [14]. Besides, other researchers based their algorithms on computational geometric techniques. For example, some researchers adopted Voronoi diagrams [15–18], some adopted convex hull or convex polygon techniques [19,20], and some adopted data partition approach [21], etc. Further more, some artificial intelligence techniques such as neural network are also adopted for circular form error evaluation [22]. Considering that the data points for circular form error evaluation are impossible to be exactly measured from the same plane in practice, Chou et al. [23] addressed this issue in three dimensions.

However, all above algorithms are just developed for evaluating the circular form error of individual circular feature. So far, there is no concept for describing the general quality status of a batch of circular features appearing in current literature. And understanding the general quality status of a batch of products is very important in the area of quality control. For mechanical parts with circular features, if a concept can be used to describe the possible worst case among a batch of circular features, it will be very helpful for people to understand the general quality status of this batch of mechanical parts. And in modern industry, products are often manufactured in batch under the same conditions. This results in many researches that focused on the study of economic or financial issues such as the calculation of production costs [24–27], the performance analysis of batch production systems [28] as well as batch production scheduling [29]. If mechanical parts with circular feature are machined in batch under the same conditions, their form errors should contain

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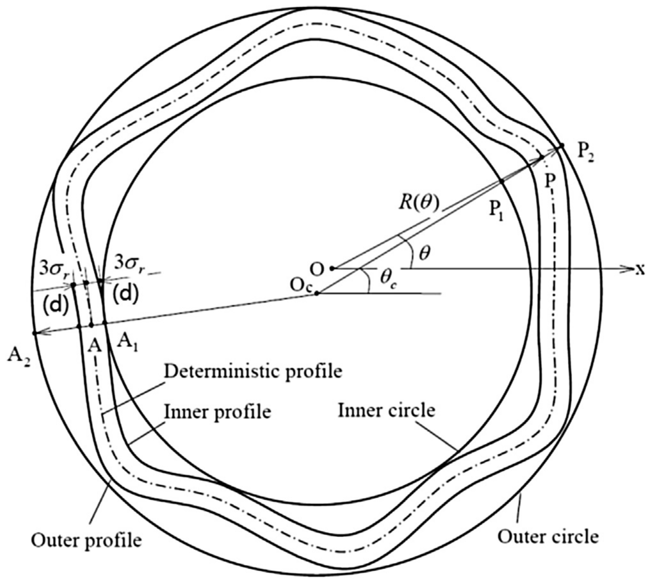

Fig. 1. Batch circular form error definition.

very similar systematic and random components. This makes it possible to estimate a circular form error value of the possible worst case by use of the data measured from one of circular features in the batch. Because such a circular form error value describes the general quality status of a batch of circular features, it can be named as batch circular form error. Apparently, if the batch circular form error is obtained, the general quality status of a batch of parts with circular features is available. The significance in practice is obvious. This paper is trying to address this issue. At first, the definitions of batch circular form error are given. Then, an evaluation algorithm is presented. Followed is the extensive analysis with simulation and experimental data. Details are reported as following sections.

2. Batch circular form error

2.1. Definitions

2.1.1. Individual circular form error

Jiang et al. [32,33] presented a methodology to evaluate the circular form error e_m of circular feature m based on a satisfactory profile confidence level P_{cl} which was dynamically determined. The basic idea can be briefly described as follows: Refer to Fig. 1 (in which O is the reference center of a polar coordinate system and O_c is the center of two concentric circles), after the deterministic profile is determined, then gradually increase the drift distance d from the deterministic profile at both sides to form an inner profile and an outer profile until the increase rate $R_{pcl}\left(=\Delta P_{cl}/\Delta d\right)$ becomes smaller than a given convergence precision ε. Then, the gap between the two concentric circles that just bound the inner profile and the outer profile completely can be defined as the circular form error and given below:

$$e_m = R_{out} - R_{in} = |O_cA_2| - |O_cA_1| \tag{1}$$

This approach would be used in this work to calculate the individual circular form error.

2.1.2. Batch circular form error with ideal conditions

As mentioned in the Introduction, the batch circular form error is used to describe the possible worst case among a batch of circular features that satisfy: (1) every circular feature has the same nominal dimension, i.e. diameter; (2) every circular feature is machined under the same conditions. Hence, the form errors of such a batch of circular features have the following attributes: (1) the systematic form error of every circular feature should be the same. In other words, the deterministic profile of every circular feature should be the same as shown in Fig. 1. (2) The random form error of every circular feature should also be the same. This means that the statistic parameters (mean μ_r and standard deviation σ_r) of the fitted residuals of every circular feature should be the same or very close to each other. But the location distribution of their residuals could be different. Under the above ideal conditions, the batch circular form error can be defined as follows: Refer to Fig. 1, if the deterministic profile is characterized, the statistic parameters (mean μ_r and standard deviation σ_r) of the fitted residuals are also available. Then, make the deterministic profile drift $3\sigma_r$ at both sides, an inner profile and an outer profile are available. Then, the gap between the two concentric circles that just bound the inner profile and the outer profile completely can be defined as the batch circular form error for such a batch of circular features and given below:

$$E_m = R_{out} - R_{in} = |O_cA_2| - |O_cA_1| \tag{2}$$

It can be seem that Eq. (2) is similar to Eq. (1). But Eq. (2) is based on $d = 3\sigma_r$ (see Fig. 1). In Eq. (2), E_m is used to denote the batch circular form error determined with circular feature m. Under the ideal conditions, all $E_m(m = 1, 2, \cdots)$ should be the same. In general, $3\sigma_r > d$. Hence, the above defined batch circular form error would be larger than the individual circular form error. i.e., $E_m > e_m$. This is why the batch circular form error is designed to describe the possible worst case among a batch of circular features.

2.1.3. Batch circular form error with realistic conditions

In practice, no matter how much effort is made to keep the manufacturing conditions the same during machining, it is impossible to make the manufacturing conditions exactly the same all the time. Besides, the measure conditions cannot keep exactly the same all the time, either. In other words, many factors coming from machining and measuring can affect the measured data. Hence, both the systematic form errors and the random form errors could be different for different circular feature.

In such a realistic situation, the two-sigma criterion is used to judge whether the circular features belong the same batch. Then the above approach with ideal conditions is used to calculate the batch circular form error E_m based on the information of circular feature m. Hence, the real batch circular form error E_m would be calculated as

$$E = \frac{\sum_{m=1}^{M} E_m}{M} \tag{3}$$

where M is the total number of the circular features in the batch.

2.2. Evaluation

Similar to the approach Jiang et al. [32,33] presented, characterization of the deterministic profile is a key step for batch circular form error evaluation. The objective for characterizing deterministic profile is to separate circular form errors into two parts: systematic and random. In this aspect, researches focused on characterizing the interested profile with Chebyshev terms or Fourier series expansion [34,35,38,37,30,36,31]. Based on Cho and Tu's work [36], Desta et al. [39] attempted to develop a robust method to characterize the circular form errors. However, their work assumed that the first Fourier component doesn't exist and the fitted residuals are independent. This assumption is not reasonable in practice. Hence, a modified model for characterizing the