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Comparative study of roundness evaluation algorithms for coordinate measurement and form data

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ABSTRACT

Roundness error is one of the significant parameters used in quality analysis and control of circular or cylindrical components. In both laboratories and industries, direct estimation of roundness error is predominantly obtained using the coordinate measuring machine and form testing device. The literature is copiously supplied with different approaches/algorithms for the implementation of the reference circles that are used to quantify roundness error. A test for their relative performance is of relevance in order to make a decision about which approach is to be used for the execution of a given reference circle. This paper replicates and compares a few selected benchmark algorithms from literature to make recommendations for the optimum choice of execution methods for Minimum Circumscribed Circle (MCC), Maximum Inscribed Circle (MIC) and Minimum Zone Circle (MZC) that are used to compute roundness error. A new computational geometric concept using reflection mapping technique was formulated to assess roundness using MIC and MZC, which has also been used in the comparison. All the algorithms were tested using the same ten sets of coordinate/profile data to establish their relative efficacy in roundness error computation. It was found that no single computation concept consistently gave the best results for all the three reference circles simultaneously. Thus, the three reference circles have been independently analyzed, and recommendations for the algorithm to be used for each of them have been presented individually.

1. Introduction

Circular components are an integral part of the majority of industrial products, especially in manufacturing industry. About 70% of all the engineering components have an axis of rotational symmetry which qualifies them to be called as circular. Roundness, also referred to as circularity, is one of the most rudimentary geometrical forms for circular objects that measures how closely the shape of a component approaches the ideal circle. As no manufacturing process is ever ideal, deviations from perfect circularity frequently occur; predominantly in machined parts. These deviations may be caused due to various reasons such as spindle run-out, erratic cutting, temperature change, insufficient lubrication and clamping distortions [1]. This out-of-roundness entails frequent problems during assembly, causing a mismatch between the mating components. Thus, accurate roundness measurement is essential to ensure correct functioning of assemblies, making roundness an important quality control parameter in manufacturing industries.

ISO 1101 [2] defines roundness as the radial separation between two concentric circles that are separated by minimum possible distance and contain all measurement points on the given profile. Four different reference circles are used to evaluate the roundness viz., Minimum Circumscribed Circle (MCC), Maximum Inscribed Circle (MIC), Minimum Zone Circle (MZC) and Least Square Circle (LSC) [3].

During the practical implementation of these reference circles, different pairs of concentric circles with minimum separation can be fit when a particular center is chosen. As shown in Fig. 1, when O_1 is selected as the center, the circle with δR_1 has the minimum separation, while opting O_2 results in the circle with separation δR_2. So, every dataset has innumerable candidate points from which this center can be picked. Now, of all the possible centers, the aim of roundness evaluation is to find that center which will give the lowest error value (in this case $\delta R_1 < \delta R_2$). This translates the roundness estimation from a problem of fitting concentric reference circles to the one finding an optimal center and radii of the reference circles. Thus, with the lack of guidelines by the ISO about the choice of the method adopted to

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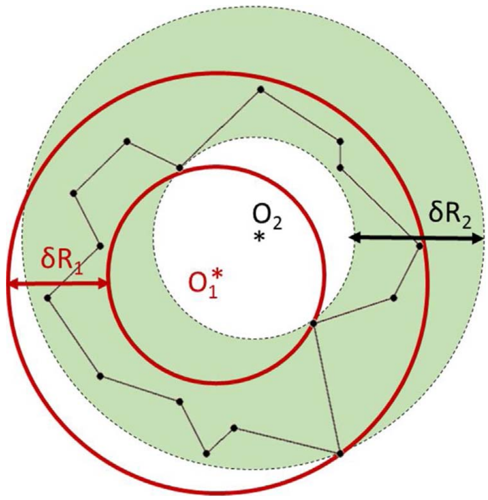

Fig. 1. Different possible candidate centers for measuring roundness.

compute roundness, estimation of roundness error remains as an open statement allowing the development of disparate approaches to find the ideal candidate center [4]. To derive these candidate centers, various computational geometric tessellation techniques like Voronoi tiling [5], Delaunay triangulation [6], and power diagram [7] are used. Out of these, the Voronoi diagram has gained popularity over time in the field of metrology.

Coordinate Measuring Machine (CMM) and form tester device are commonly used to collect the sampling points to form the required profile and estimate the roundness error. In most cases, all these machines are equipped with the option to evaluate the roundness error using all the reference circles. Hence, one is required to use some form of heuristic to make a decision about the reference circle to be used for a particular application. In practice, evaluation of roundness using MZC complies closely with the ISO definition of roundness and often gives the least value of roundness error making it useful in gauging tolerance. Despite this fact, MCC and MIC reference circles are used for shafts and holes respectively to adhere to functional requirement and prevalent industrial practice [8,9]. LSC is a popular approach for quick quality checks owing to its robustness and computational efficiency. However, it has the downside of not being the default recommendation according to ISO standard. Thus, each reference circle has its own significance and application for roundness computation. Once the reference circle for a particular application has been decided, it becomes mandatory to select the best possible algorithm for the execution of the selected reference circle. This task is of particular significance from the perspective of a metrology system developer. The work presented here is expected to be of help in making the choice of algorithm to be used for implementation of a given reference circle.

The objective of the present work is to make algorithm recommendations for the execution of MCC, MIC, and MZC through a brief sampling of algorithms from the literature and comparing their accuracy in roundness error computation. The work is intended to suggest algorithm(s) that can be adopted to implement a specific reference circle and not to provide guidelines on the choice among the reference circles to be used for a particular application. The nature of algorithms and their execution methods for LSC are quite different from other three reference circles and are not covered in the present comparison study. A new technique named reflection mapping has been developed by taking cues from maximum radius inscribing limacon approach of Chetwynd [10,11] to quantify roundness error using MIC and MZC. It is also included in the comparative study and has been juxtaposed against the benchmarks to arrive at the choice of algorithms for practical applications in measurement devices. The three chosen benchmark algorithms are based on numerical approach and computational geometric technique; one [12] based on the former and two [13,14] based on the latter. Ten sets of data, each for CMM and form tester were used as input for comparison. The chosen algorithms have been separately tested on data obtained from both machines as the nature of the datasets differs in terms of the extent of undulation in the measured profile. This comparison helps in establishing the effectiveness of each algorithm in adapting to different data input types.

2. General approach to roundness evaluation

When it comes to developing algorithms for estimation of roundness error, there are numerous ways in which people have approached this. Despite the variety of approaches to tackling this problem, there are a few basic patterns which most of them follow. This common thread runs through algorithms developed for both CMM and form tester data.

A minimum number of four points are required to fit a pair of concentric circles. This can be done in 3 possible combinations of 1-3 pair, 3-1 pair and 2-2 pair where each number indicates the number of points on the outer and inner circle. They represent the MIC, MCC and MZC reference circles respectively as shown in Fig. 2. There are two types of convex hulls viz., Outer Convex Hull (OCH) and Inner Convex Hull (ICH) used to cull out candidate points from the raw input data. MCC evaluation uses the OCH which is the smallest polygon enclosing the given dataset completely. Many methods have been developed for evaluation of OCH, but it has been found that it remains unique for a given dataset [11]. So, most MCC algorithms aim to bring refinement in the processes following OCH construction which use these as initial points. Similarly, MIC uses ICH which is the largest polygon fit to the data such that all the points lie either on or outside it. Unlike OCH, the ICH is not unique [13] for a given set of points.

Once the candidate points are chosen for the respective reference circles, the algorithms generally iterate over the outer convex hull for MCC and the inner convex hull for MIC to eliminate the number of candidate centers in successive steps. A circle is fitted to the candidate

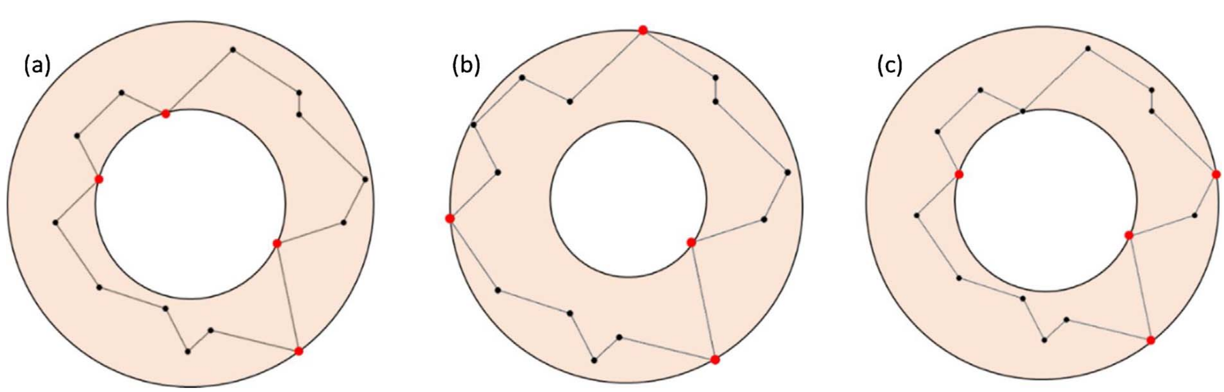

Fig. 2. Three classes of concentric circle fits: (a) 1-3 pair (b) 3-1 pair (c) 2-2 pair.