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Optimal blind sampling strategy for minimum zone roundness evaluation by metaheuristics

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ABSTRACT

The minimum zone tolerance is a non linear method to find a global solution to the roundness evaluation problem. Metaheuristics such as genetic algorithms, ant colony systems and particle swarm optimization concurrently process a set of solution candidates (chromosomes, ants, particles etc.) within a given search-space. Computation experiments carried out with an effective genetic algorithm have shown that the optimal sampling strategy providing sufficient accuracy at acceptable processing time represents a compromise between number of sample points and search-space size. An estimate of the neighborhood of the centroid containing the minimum zone center is given.

1. Introduction

The growing complexity of shapes of manufactured parts and assembly tasks and the increase of performance demand to mechanical products requires high-speed inspection. Evaluation of form errors of machined parts is fundamental in quality inspection to verify their conformance to the expected tolerances. Performance of methods have been reviewed in [1].

Form tolerance is evaluated with reference to a Euclidean geometric feature, i.e. a circle in the case of roundness (also known as circularity). Roundness is a typical geometric form to be inspected as well as other typical forms such as straightness, flatness and cylindricity.

The most used criteria to establish the reference circle are: the least-squares method (LSQ), the maximum inscribed circle (MIC), the minimum circumscribed circle (MCC) and the minimum zone tolerance (MZT).

The use of a particular data fitting method depends on the required application, e.g. MIC and MCC can be used when mating is involved. The LSQ is one of the methods used by Coordinate Measuring Machines (CMM). It is efficient in computation and can be used with a large number of measured points, but the roundness error determined is larger than those determined by other methods, such as the MZT. Therefore, good parts can be rejected resulting in an economic loss. The MZT meets the standard definition of the roundness error, as reported in ISO 1101 [2]. It determines two concentric circles that contain the roundness profile and such that the difference in radii is the least possible value. Fig. 1 shows two pairs of concentric circles that include the sample points centered respectively at c_1 and c_2 and where Δr_1 and Δr_2 are their difference in radii. Once the MZ center is found, the minimum zone error can be considered as the roundness error.

The MZT is a non linear problem and two approaches have been proposed in the literature: computational geometry techniques and solutions of a non linear optimization problem. The first approach is, in general, very computationally intensive, especially, when the number of data points is large. One of these methods is based on the Voronoi diagram [3]. The second approach is based on the minimization of the minimum zone error as a function of the MZ center, but the inconvenience is that this function has several local minima. Some examples are: the Chebyshev approximation [4], the simplex search/linear approximation [5,6], the steepest descent algorithm [7], the particle swarm optimization (PSO) [8,9], the simulated annealing (SA) [10], and genetic algorithms (GAs) [11–14].

Xiong [15] develops a general mathematical theory, a model and an algorithm for different kinds of profiles including roundness where the linear programming method and exchange algorithm are used. As limaçon approximation is used to represent the circle, the optimality of the solution is however not guaranteed.

A strategy based on geometric representation for minimum zone evaluation of circles and cylinders is proposed by Lai and Chen [16]. The strategy employs a non-linear transformation to convert a circle into a line and then uses a straightness evaluation schema to obtain minimum zone deviations for the feature concerned. This is an approximation strategy to minimum zone circles.

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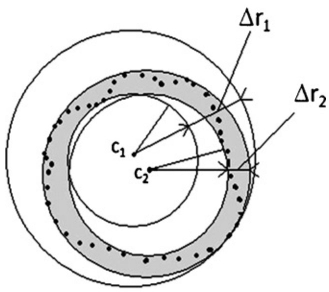

Fig. 1. MZ error E_{MZ}. c_1 and c_2 are possible locations of the centers of the two concentric circles. Δr_1 and Δr_2 are the differences in radii. If the minimal difference in radii Δr_2 is the E_{MZ}, c_2 is the MZ center.

Wang et al. [17] and Jywe et al. [18] present a generalized nonlinear optimization procedure based on the developed necessary and sufficient conditions to evaluate roundness error. To meet the standards, the MZ reference circles should pass through at least four points of the sample points. This can occur in two cases: (a) when three points lie on a circle and one point lies on the other circle (the 1–3 and the 3–1 criteria); (b) when two points lie on each of the concentric circles (the 2–2 criterion). In order to verify these conditions the computation time increases exponentially with the dataset size. Gadelmawla [19] uses a heuristic approach to drastically reduce the number of sample points used by the min–max 1–3, 3–1 and 2–2 criteria.

Samuel and Shunmugam [20] establish a minimum zone limaçon based on computational geometry to evaluate roundness error; with geometric methods, global optima are found by exhaustively checking every local minimum candidate. Moroni and Petro [1] propose a technique to speed up the exhaustive generation of solutions (*brute force algorithm*), which starts with a single point and increases one sample point at each step in order to generate all the possible subsets of points, until the tolerance zone of a subset cover the whole dataset (*essential subset*).

A mesh based method with starting center on the LSC, where the convergence depends on the number of mesh cross points, representing a compromise between accuracy and speed, is proposed by Xianqing et al. [21].

The strategy to equally spaced points sampled on the roundness profile is generally adopted in the literature. Conversely, in previous works the authors developed a cross-validation method for small samples to assess the kind of manufacturing signature on the roundness profile in order to detect critical points such as peaks and valleys [22,23]. They use a strategy where a next sampling increasing the points near these critical areas of the roundness profile.

In [24], some investigations proved that the increase of the number of sample points is effective only up to a limit number. Recommended dataset sizes are given for different data fitting methods (LSQ, MIC, MCC, MZT) and for three different out-of-roundness types (oval, 3-lobing and 4-lobing). Similar works are [25,26] in which substantially the same results are given.

A sampling strategy depends on the optimal number of sample points and the optimum search-space size for best estimation accuracy, particularly with datasets that involve thousands of sample points available by CMM scanning techniques. In this paper, the sampling strategy problem tailored for a fast genetic algorithm to solve the MZT problem is addressed. To achieve more general results, the sampling strategy used in this work can be defined as *blind* according to the classification in [27]. By sampling strategy not only the number and location of sample points on the roundness profile is addressed, but also their use by the data fitting algorithm [28].

Based on current experience, only few contributions are available in the literature regarding the sampling parameters, particularly with genetic algorithms. In [12] the search-space is a square of fixed 0.2 mm side, in [14] it is 5% of the circle diameter and center. In [11], the side is determined by the distance of the farthest point and the nearest point from the mean center. In [13] it is the rectangle circumscribed to the sample points. The optimal selection of the number of sample points and the search-space represent the main focus of current work.

2. Genetic algorithms for the MZT problem

To experimentally assess the sampling strategy with metaheuristics (such as genetic algorithms, ant colony systems, particle swarm optimization, and taboo search) a previously optimized genetic algorithm [14] has been selected. Genetic algorithms constitute a class of implicit parallel search methods especially suited for solving complex optimization or non-linear problems. They are easily implemented and powerful being a general-purpose optimization tool. Many possible solutions are processed concurrently and evolve with inheritable rules, e.g. the elitist or the roulette wheel selection, so to quickly converge to a solution, which is very close or coincident to the optimal solution.

Genetic algorithms maintain a population of center candidates (the *individuals*), which are the possible solutions of the MZT problem. The center candidates are represented by their *chromosomes*, which are made of pairs of x_i and y_i coordinates. Genetic algorithms operate on the x_i and y_i coordinates, which represent the inheritable properties of the individuals by means of genetic operators. At each generation the genetic operators are applied to the selected center candidates from current population in order to create a new generation. The selection of individuals depends on a fitness function, which reflects how well a solution fulfills the requirements of the MZT problem, e.g. the objective function.

Sharma et al. [29] use a genetic algorithm for MZT of multiple form tolerance classes such as straightness, flatness, roundness, and cylindricity. Because of the small dataset size (up to 100 sample points), there is no need to optimize the algorithm performance, by choosing the parameters involved in the computation.

Wen et al. [30] implement a genetic algorithm in real-code, with only crossover and reproduction operators applied to the population; thus in this case mutation operators are not used. The algorithm proposed is robust and effective, but it has only been applied to small samples.

A fast genetic algorithm with convergence speed greater than 0.1 μm per 30 generations, within a selected stop condition, has been developed for large manufacturing samples and validated by certified software in [14]. The authors state that larger datasets require higher population size and not significantly affect the probability of crossover within a wide range. They conjecture that mutation is not a fundamental operator.

Table 1 lists all the parameters with their mechanism and value used by the data fitting algorithm proposed here. The optimal values of the genetic operators P_s, P_c and P_m are taken from [14]. The genetic algorithm starts with a population of 70 center candidates (P_s), randomly chosen in a search-space $S_{r(x,y,\theta_i)}$ centered in C_n defined later in expression (2). At each generation the center candidates with their minimum zone reference circles and difference in radii are simultaneously evaluated for fitness by expression (1) also introduced later.

3. Problem formulation

The minimum zone error E_{MZ} is the solution of the following optimization problem [14]:

$$\min\left[\max_{\theta_i=i\times(2\pi/n),\ \ i=1,\ldots,n} r(x,y,\theta_i) - \min_{\theta_i=i\times(2\pi/n),\ \ i=1,\ldots,n} r(x,y,\theta_i)\right] \quad \text{subject to } (x,y)\in S_{r(x,y,\theta_i)} \tag{1}$$