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Evaluating minimum zone flatness error using new method—Bundle of plains through one point

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ABSTRACT

An attempt was made to create a new software solution for evaluating minimum zone (MZ) based flatness error using data acquired from a coordinate measuring machine (CMM). The authors tried to exploit one very useful characteristic of a reference plane for evaluating flatness error. Namely, it is shown that only one point located within a "cloud" of points can be used to generate reference planes for the purpose of evaluating flatness error. The method is named One Point Plane Bundle Method (OPPBM). A solution was created using exclusively basic analytic geometry relations/transformations and a general purpose worksheet tool. The results show that this solution can be used to determine very usable MZ flatness error values, which are significantly lower than values provided by the least square method. Execution times are also reasonable and acceptable. The method has been validated using the data from reference literature and experimental data measured by a CMM.

1. Introduction

For satisfying a number of functional requirements related to mechanical assemblies, flatness tolerances are often applied in workpiece specifications. Conformance with specifications is verified in accordance with appropriate standards [1]. Thanks to their flexibility, coordinate measuring machines (CMM) are the most effective tool in measuring systems. They are highly effective in verifying all of the workpiece macro-deviations because they operate through two independent phases [2]. The first phase involves physical extraction of a finite sample size using a particular probe. The selected sample points should represent the surface as accurately as possible. The second phase includes feature fitting for the purpose of evaluating associative geometry. The measurement result represents the difference between nominal and associative geometry. Thus, this phase has a key impact on the achieved measurement error/uncertainty. Two methods for obtaining associative geometry are used: minimum zone (MZ) and least square (LS) method. Although the LS method is statistically based, more often used and the approach easy to carry out, the MZ based evaluating form tolerance is recommended by ISO 1101 [3] (accurate version of ISO 1101 is from 2012, at the moment being revised).

Thus, the problem of evaluating the MZ flatness error has attracted attention of researchers for a long time. Murthy and Abdin [4] were among the first in 1980 to describe methods based on Monte Carlo simulation, normal least square fit, simplex search and spiral search used to evaluate surfaces. In the study of Shunmugam [5] it has been noted that the least square based methods for evaluating flatness errors do not always yield minimum value. Dhanish and Shunmugam [6] proposed in their study linear Chebyshev approximation to solve the MZ based approach for evaluating various surface form errors. Huang et al. [7] proposed a MZ based algorithm for evaluating flatness errors called the control plane rotation scheme. Kanada and Suzuki [8] briefly described and compared five linear methods used for evaluating straightness errors. In Ref. [9] the same authors described some nonlinear techniques used for evaluating flatness errors. Cheraghi et al. [10] presented a method for evaluating straightness and flatness errors based on linear programming/convex hull procedure. They also presented test data and results. Several years later Samuel and Shunmugam [11] also used convex hull procedures for the same purpose. Sharma et al. [12] were among the first to introduce the use of genetic algorithms for evaluating form tolerances. Zhu and Ding [13] also contributed to the development of linear programming methods

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in reaching minimum zone solutions. Weber et al. [14] introduced unified linear approximation technique for evaluating form errors. In the years to follow, linear programming techniques (e.g. Portman et al. [15]) and the use of genetic algorithms (e.g. Wen et al. [16] and Cui et al. [17]) for evaluating form errors were improved. Calvo et al. [18] provided a brief retrospective of the proposed methods for evaluating form errors and proposed a new vectorial method based on MZ.

The methods described in these and similar references are more or less complex, more or less time consuming, described with more or less clarity and more or less easy to implement. However, their complexity and/or the amount of information provided, in most cases, narrow the group of potential users.

This paper is intended to present a very simple solution to the problem of evaluating flatness errors based on MZ. What is more, nowadays, when the use of information technology is widely available, it is indeed recommended that the use of standard software tools should be sufficient for basic implementation of a method. Last, but not the least, the time needed for execution and acquiring the results is also one of the most important user requirements.

Because the method is based on generating a bundle of planes through one point, it has been named One Point Plane Bundle Method (OPPBM).

2. Method used

The method is based on a very useful property of a reference plane used for evaluating flatness error. Namely, coordinates of a plane normal vector are the only three parameters that affect flatness error value. Actual plane position is not relevant, because its *orthogonal translations do not affect flatness at all*. It means that in a plane equation given by formulas (1) and (2) as [19]:

$$Ax + By + Cz + D = 0 \tag{1}$$

or

$$z = -\frac{Ax + By + D}{C} \tag{2}$$

where A, B and C are coordinates of a plane normal vector and D is a constant defining the position of a plane, parameter D is irrelevant and does not affect evaluation of flatness error. It means that taking any plane with a particular normal vector defined by parameters A, B and C results in the same evaluation of flatness error (location of a particular plane once determined by normal vector rotation and the fact that point A belongs to the plane, defines its particular value of parameter D which is then used later to calculate orthogonal distances from the generated planes from a bundle and evaluate flatness error – see formulas (12) and (13)).

The literature review did not show this information. Here is the proof.

Suppose α is a reference plane (plane parallel to envelope planes) for evaluating flatness (Fig. 1). CMM reports n points measured from a surface being evaluated (point cloud on the left). They have appropriate orthogonal projections on plane α' (point cloud on the right).

Fig. 2 represents a projection of CMM points to plane α', perpendicular to plane α (as seen from the position designated in Fig. 1). Lines a (which is an intersection of planes α and α') and b (which belongs to plane α') are also perpendicular. An observing position designated on the left side of Fig. 1 with an "eye-like" symbol followed by an oriented dash-line enables observing actual values being components of flatness error (see Fig. 2).

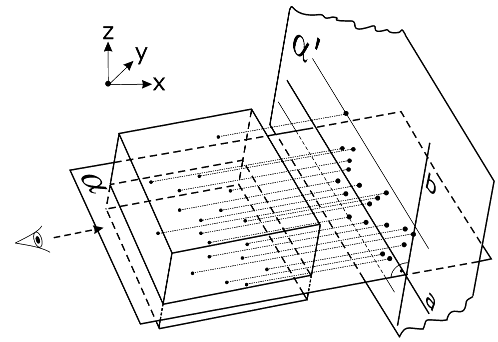

Fig. 1. Points from CMM with a parallelogram, reference plane α and perpendicular plane α'.

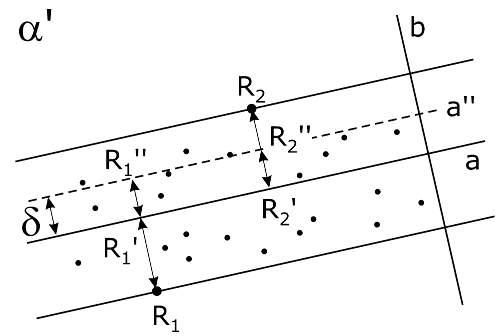

Fig. 2. Projection to plane α'.

Flatness error R is calculated using (3) (see also Fig. 2), assuming that R_1 and R_2 are the points with the largest orthogonal distances from plane α:

$$R = \overline{R_1R_1'} + \overline{R_2R_2'} \tag{3}$$

If plane α is translated for any δ to a new position a'' parallel with the previous (assuming δ small enough to locate a'' somewhere within the point "cloud"), flatness error is then calculated as:

$$R' = \overline{R_1R_1''} + \overline{R_2R_2''} = \overline{R_1R_1'} + \delta + \overline{R_2R_2'} - \delta = R \tag{4}$$

As a consequence of this equality, changing a point containing the reference plane and keeping the same normal vector (which is the same as orthogonal translation of a plane) does not affect flatness error value. In other words, it makes calculating flatness errors according to a predefined plan of experiment using a particular number of points completely unnecessary. Reference planes could be generated through *only one point*, wherever selected within the parallelogram defined by maximum and minimum coordinates of points reported by a CMM. It guarantees obtaining the optimum flatness value for the given numbers of steps used for reference plane rotation which is defined by numbers of calculating cycles.

Indirect proofs of this claim can be found in studies [16] and [18]. Namely, considering formulas used for calculating flatness error (as two perpendicular distances from two points on two envelop planes) makes it obvious that flatness error evaluation is influenced by the plane normal vector parameters, but not by the constant in the plane equation (which is determined by coordinates of a point on the plane). This is completely tested and is found accurate as explained later in this paper in Section 3.

The parallelogram determined by the lowest/highest, leftmost/rightmost and closest/farthest coordinates of the CMM reported points (as seen from the origin) is presented in Fig. 1. The