THE SELECTION OF RADIUS CORRECTION METHOD IN THE CASE OF COORDINATE MEASUREMENTS OF A TURBINE BLADE

Andrzej KAWALEC[1], Marek MAGDZIAK[2]

1 Rzeszów University of Technology, W. Pola 2, 35-959 Rzeszów, Poland, ak@prz.edu.pl
2 Rzeszów University of Technology, W. Pola 2, 35-959 Rzeszów, Poland, marekm@prz.edu.pl

Abstract:

The objective of the research presented in the paper is the selection of suitable probe radius correction method in the case of coordinate measurements of a turbine blade. The investigations are based on theoretical analysis of geometric data and on further computer simulation of measurements and data processing. In the paper two methods for computing coordinates of corrected measured points are verified. Those so-called local methods of probe radius correction are based on the 2nd degree and the 4th degree Bézier curves. They are dedicated first of all to coordinate measurements of free-form surfaces which are characterized by big values of curvature, e.g. those surrounding the leading and trailing edges of a turbine blade. Numerical simulations are done for several models of the transverse sections of turbine blades with diversified magnitudes of radii of curvature. There are considered both manufacturing deviations and coordinate measurement errors of each examined profile of turbine blade. Moreover, the paper presents an algorithm concerning computations of data which extends the set of standard algorithms used for the analysis of coordinate measurements of a turbine blade developed by Carl Zeiss for its coordinate measuring machines and coded within the measurement software *Calypso* and *Blade Pro*. The paper shows how to implement the developed algorithms of probe radius correction within the standard CMM software by using parametric programming option PCM available in the measurement software *Calypso*.

Keywords: CMM-metrology, probe radius correction, polynomial interpolation.

1. INTRODUCTION

Probe radius correction process is the fundamental stage in contact coordinate measurements of products, especially those containing free-form surfaces, using coordinate measuring machines (CMMs). Correction procedures consist in computing the coordinates of corrected measured points based on the coordinates of indicated measured points being the centers of spherical stylus tip of measurement probe [1-3]. The methods of correction may base either on nominal or actual vector normal to the measured curve or surface. Corrected measured points should be actual contact points between the stylus tip of measurement probe and measured object. Therefore, the direction of tip correction vector should conform the direction of actual normal vector at considered measured point of measured object. One approach consists in application of special probe with a force sensor [4]. The other approach relies on the application of numerical algorithms allowing to compute approximate normal vectors based on the geometric model of measured object.

The analysis of measurement errors caused by application in computations of nominal normal vector is given in [5]. In paper [6] a method of probe radius correction based on triangular network defined by indicated measured points located on free-form surface is described. Normal vector is computed as a vector product of vectors representing the edges of triangles. Paper [7] extends the method given in [6] by introducing weight coefficients. They are used to calculate four auxiliary vectors. An actual normal vector is computed from those auxiliary vectors.

In paper [8] it is shown that wrong correction of the radius of stylus tip of probe causes significant errors in scanning measurements on CMMs, especially in the case of relatively small measured objects, compared to the radius of stylus tip. Therefore, in papers [8-10] a method of computing corrected measured points is presented, based on determination of the approximate envelope of scanned curves built of arcs being parts of the stylus tip profile in successive measurement locations of the probe.

In order to verify algorithms used for probe radius correction a virtual simulator of scanning measurements was developed in [11]. It computes indicated measured points for the corresponding corrected measured points.

The method of probe radius correction presented in paper [12] applies kriging procedure for the interpolation of indicated measured points. Corrected measured points are generated using vectors normal to the surface representing successive locations of the center of stylus tip. Kriging interpolation is also used for probe radius correction shown in paper [13].

Two methods of probe radius correction leading to an iterative algorithm are shown in paper [14]. In the first one the shape of measured surface is approximated using triangular surface patches which are divided into smaller surface patches after checking whether such linear approximation of curvilinear measured surface satisfies the requirement of assumed approximation accuracy. If the accuracy is not achieved, the surface patches are subdivided according to new additional measured points. In the second method, Bézier cubic surface patches are applied for free-form surface generation which can be further divided into smaller ones without additional measurements.

The algorithms of probe radius correction based on B-Spline or NURBS (Non-uniform Rational B-Spline) are presented in papers [15,16]. Indicated measured points are treated at the beginning of the developed in [15] algorithm as the control points of free-form surface. In the next stage normal vectors are calculated in direction normal to the surface interpolating indicated measured points. Based on that, corrected measured points are generated. Extended algorithm is shown in paper [16] where either B-Spline or NURBS surfaces are used for approximation. Proposed algorithm fits a surface to measured points in consecutive iterations by suitable modification of control points or weight coefficients.

The correction method of probe radius given in paper [17] also uses NURBS surfaces generated from indicated measured points approximated with least squares method. Measured points are fitted to some offset surface computed from the nominal model of measured surface. This step is made in order to determine the relation between the coordinate systems of used CMM and measured object. For smoothing the sequence of measured points suitable filtering of data is applied. Each indicated measured point is then replaced with the nearest point from the approximating surface. Probe radius correction with NURBS curves is shown in paper [18]. Indicated measured points are interpolated using NURBS curves. Next, those curves are used for generation of the surface associated with the successive locations of the centers of stylus tip.

The direction of tip correction vector can be determined from the vector product of two auxiliary vectors. Each of them is computed from the two sequences of points containing two points located on both sides of considered indicated measured point [19]. Different approach is given in paper [20], where tip correction vector is computed at the central point of the set of nine indicated measured points. For that purpose the 2nd degree Bézier surface patch is used as the interpolation model. In paper [21] an extended algorithm is presented for computing tip correction vector based on two moving masks of three or five consecutive indicated measured points along each direction of constant parameters u and v. The unit normal vector to the surface is computed from the vector product of two vectors tangent to the interpolating Bézier or B-Spline curves.

In paper [22] a method is presented for coordinate measurements of external profiles of porous objects. Estimated direction of normal vector is computed from the tangentially extrapolating cubic spline used for predicting the trend of considered curve.

Published methods for probe radius correction fall into three main categories. They use information from: (i) the probe with force sensors, (ii) nominal data from the CAD model of measured object, (iii) interpolation and approximation of indicated measured points surrounding the one at which the tip correction vector has to be determined. Among advantages they also exhibit specific disadvantages. One of the disadvantages is that the computational procedures are sensitive to the input data from the neighborhood of considered point and to applied models of interpolation, approximation and filtering of the measurement data. Moreover, in the case of fitting data to some assumed model both the results and their cost depend on the effectiveness of applied optimization methods [23].

Therefore, considering smoothing capabilities of Bézier functions, in this paper two suitable local methods useful for the determination of corrected measured points are developed and applied for the simulation of coordinate measurements of a turbine blade. The results of application of both methods are compared with each other and with nominal data. The way of implementation of the algorithm into CMM standard software is also described.

2. PROBE RADIUS CORRECTION

2.1 Methods of Computing Probe Radius Correction

In order to determine corrected measured points it is required to know the vectors normal to investigated profile related to the indicated measured points which are coincident with measurement locations of the center of stylus tip. Therefore, successive measurement locations of the center of stylus tip are interpolated using the 2nd degree (**method A**) and the 4th degree (**method B**) Bézier functions. The following stage consists in computing normal vectors and corrected measured points. Deviations between the accurate, i.e. already known, points from the profile of turbine blade and corrected ones are determined along the whole considered profiles of turbine blade and used in further analysis.

2.2 Model of 2D Profiles of a Turbine Blade Used for Simulations

The planar model of turbine blade profile used for simulations is built of four arcs with straight internal angles fulfilling G^2 continuity conditions at joining points. They compose a closed contour, in which $R1$, $R2$, $R3$ and $R4$ represent the radii of curvature associated with leading edge, sucking face, trailing edge and thrust face of blade, respectively. The contour consists of both concave – on thrust face – and convex curves – other faces – with significant differences between the radii of curvature.

Developed geometric model allows for easy computation of the corresponding offset contour because normal directions to the modeled contour are determined by half lines passing through selected points on the arcs and starting at the centers of related circles. Both x and y coordinates of points on the offset contour are independently modified using the noise with normal distribution $N(\mu,\sigma^2)$ of mean μ and variance σ^2. That noise maps both manufacturing deviations and coordinate measurement errors. Such offset contour modified with the noise represents the real path for the centers of stylus tip of measurement probe.

2.3 Results of Simulations

The maximum Δmax, median Δmed and average deviations Δav arising from the application of the methods A and B are compared with each other. The differences between the average deviations $\Delta av,B - \Delta av,A$ resulting from using the methods B and A are shown in Figs. 1–3. They are obtained for some representative turbine blade profiles disturbed with the noise of normal distribution $N(\mu,\sigma^2)$ of mean $\mu = 0$ and different magnitudes of standard deviation varying in range $\sigma = 0.02(0.02)0.1$ mm.

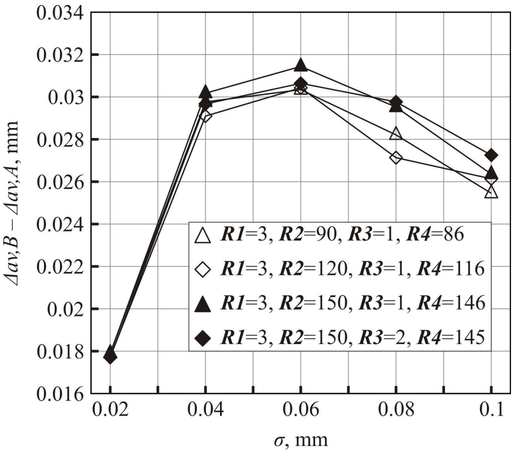

Fig. 1: The differences between the average deviations $\Delta av,B - \Delta av,A$ resulting from using the methods B and A for the profiles with the leading edge radius $R1 = 3$ mm

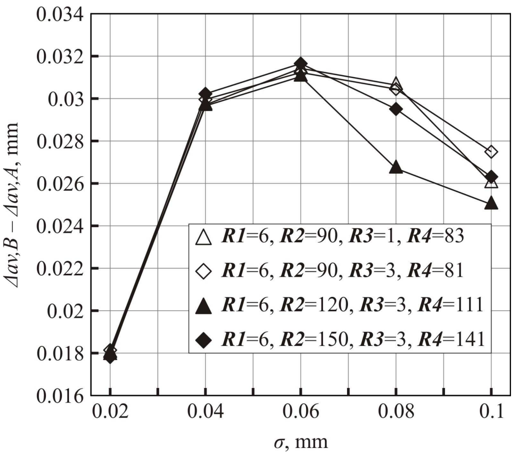

Fig. 2: The differences between the average deviations $\Delta av,B - \Delta av,A$ resulting from using the methods B and A for the profiles with the leading edge radius $R1 = 6$ mm

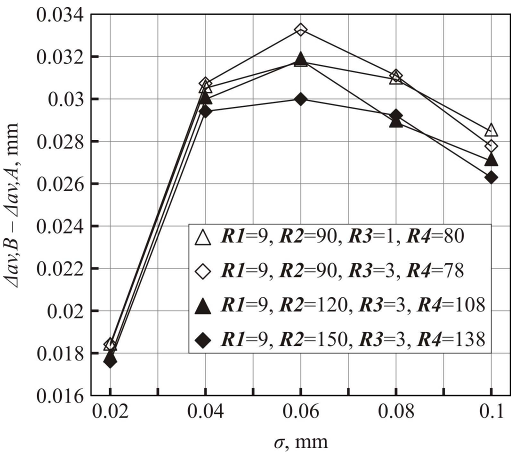

Fig. 3: The differences between the average deviations $\Delta av,B - \Delta av,A$ resulting from using the methods B and A for the profiles with the leading edge radius $R1 = 9$ mm

The average deviations Δav between the corrected measured points and related nominal points computed for various profiles and standard deviations of normal noise σ using the methods A and B based on 2nd degree and 4th degree Bézier polynomials, respectively, are shown in Table 1.

Table 1: Selected average deviations $\Delta av,A$ and $\Delta av,B$

***R1*, mm**	***R2*, mm**	***R3*, mm**	***R4*, mm**	***σ*, mm**	***Δav,A*, mm**	***Δav,B*, mm**
3	90	1	86	0.02	**0.0787**	**0.0967**
				0.04	**0.2205**	**0.2503**
				0.06	**0.3438**	**0.3742**
				0.08	**0.4219**	**0.4501**
				0.1	**0.4755**	**0.5010**
3	120	1	116	0.02	**0.0784**	**0.0961**
				0.04	**0.2194**	**0.2485**
				0.06	**0.3449**	**0.3753**
				0.08	**0.4277**	**0.4549**
				0.1	**0.4810**	**0.5071**

2.4 Discussion

From obtained results it follows that both average deviations $\Delta av,A$ and $\Delta av,B$ increase with raising standard deviation of applied noise σ. The differences $\Delta av,B - \Delta av,A$ between the deviations grow from approximately *0.018* mm until the standard deviation σ reaches *0.06* mm. For bigger magnitudes of σ the differences $\Delta av,B - \Delta av,A$ diminish with various intensities, depending on the dimensions of blade profile.

3. IMPLEMENTATION OF AN ALGORITHM FOR PROBE RADIUS CORRECTION INTO STANDARD CMM SOFTWARE

3.1 Steps Made Only Once

1. Launch the *Calypso* software which is the software for the Carl Zeiss CMM. Create a new measurement plan.
2. Define *Blade macro* within the *Calypso* software.
3. Export nominal curves representing transverse sections of a turbine blade to an XML file using the *Blade macro*. Measurements are done by utilizing the *Curve 3D* features.
4. Create a specification file within the *Blade Pro* software. Determine transverse sections of a turbine blade for measurements. Specify measurement and location characteristics of investigated blade for all transverse sections.

3.2 Steps Made Repeatedly

5. Launch the *Blade Pro* software and select the specification file created in step 4.
6. Run *Blade macro* within the *Calypso* software.
7. Make coordinate measurements of investigated blade.
8. Save the results of coordinate measurements of turbine blade – coordinates of indicated measured points – into a VDA file. Edit the VDA file and create data for an external program for computing corrected measured points according to the selected method of probe radius correction.
9. Export the magnitude of stylus tip radius from the *Calypso* software to the data file created in previous step.
10. Select the probe radius correction method. Update the data file for computing corrected measured points.

11. Launch the external program from inside the *Calypso* software and compute corrected measured points from the data updated in previous step. Save the results into some XML file.
12. Create, in the *Blade Pro* software, a file containing the results of coordinate measurements of investigated blade.
13. Analyze, in the *Blade Pro* software, collected results of measurements concerning investigated blade.

4. CONCLUSIONS

Coordinate measurements of free-form curves and surfaces require application of proper probe radius correction method. It is directly connected with the determination of the direction of tip correction vector. Such vector can be successfully computed as a vector normal to the Bézier curve of 2^{nd} and 4^{th} degrees interpolating the locations of the centers of stylus tip.

From preformed investigations it follows that for investigated models of turbine blade profiles the correction method based on 2^{nd} degree Bézier curves gives smaller errors than the one based on 4^{th} degree Bézier curves. That difference grows until the standard deviation of normal noise σ reaches *0.06* mm and decreases for bigger values of σ. Therefore, in order to diminish the errors of coordinate measurements it becomes justified to select the right method of probe radius correction using an external program. The selection of the method should consider, among others, the variations of shape of measured curves and surfaces associated with manufacturing deviations and measurement errors.

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