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STUDY OF THE INFLUENCE OF SURFACE FORM ERRORS ON THE FITTING UNCERTAINTY IN COORDINATE MEASUREMENTS

In coordinate measurements theoretical substitute features are determined using discrete data which are the coordinates of the measurement points. The fitting results have an uncertainty influenced by coordinate measuring machine, surface geometric errors and number and distribution of measurement points. The fitting uncertainty affects both the precision of the tolerance interval to be determined as well as the width of the conformity zone. The paper presents the investigations results of the influence of surface geometric errors on the fitting uncertainty of a least square circle. The investigations were performed on a surfaces superimposed by random form errors and systematic form errors for a various number of sample points uniformly distributed around the entire circle as well as on circular sectors defined by angles of different values.

Key words: coordinate measurements, substitute feature, uncertainty, surface form errors

1. INTRODUCTION

To ensure the production of high precision machine parts constitutes an essential element of modern manufacturing processes. Product quality inspections involve measurements of product dimensions and deviations followed by verifications of product specifications.

At present coordinate measuring machines (CMMs) appear to be most technologically advanced and universal tools commonly used to perform all kinds of precision measurements. The versatility allows CMMs to inspect a wide range of features and part types. Another advantage of CMMs is that the software designed to measure the dimensions of a specific object can be used a large number of times. As a result CMMs can be applied in industry for dimensional control of 3D objects of high complexity.

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In essence the coordinate measuring technique involves determining the location of discrete, finite number of sample points on the surface of the studied object. As a result, we obtain a set of data that are the coordinates of each and every measured point on the surface. The next step involves best fit i.e. determining a theoretical substitute feature. The measurement points collected from the true surface do not fit perfectly to the substitute feature. The best-fit results are affected by three major factors: the algorithm of the best fit, the number and distribution of measurement points and finally the effects of both CMM and surface geometry errors.

Fitting uncertainty is important not only due to the dimensional analysis of the surface geometrical elements but also affects the accuracy of determining the datum features of the workpiece coordinate system [4].

A large number of theoretical investigations and experiments concerning the impact of CMM errors [3], best fit algorithms [1] and sampling strategies [2] on the coordinate measurement results have been carried out. However not much has been published on the subject measurement uncertainties caused by surface geometry errors.

Even if a perfect best-fit algorithm is used, surface geometry deviations as well as CMM errors will create some errors in the fitting process. Fitting uncertainty will decrease the tolerance interval determination accuracy and thus affect the conformity zone, as shown in Fig. 1.

![Fig. 1. Effect of uncertainty on the measurement results assessment](image)

1 – specification interval, 2 – conformity interval, 3 – nonconformity interval, 4 – uncertainty intervals, U – expanded uncertainty


Uncertainty assessment can be used to diagnose the fitting process in order to indicate the precision of determining of tolerance zones.

Surface geometry errors of the analyzed object are generally much greater than the uncertainties of the measuring instrument. In this experiment, it has been assumed that the machine error is insignificant that it has no influence on the fitting results. The most commonly used surface geometry element for machine parts is the circle. It can be applied to describe a large number of internal and external cylindrical surfaces. The uncertainty of determining substitute features involves the uncertainty of defining the centre of the circle in X and Y di-
rections as well as the uncertainty of the circle diameter and tolerance zone for both the diameter and form errors.

In this paper the results of experimental investigations showing the influence of surface form errors on the uncertainty of determining both the centre $X$, $Y$ coordinates and the diameter of the substitute least square circle (LSC) are presented. The investigated cylindrical surfaces showed similar form errors values, however they significantly differed in the very nature of the errors. Various numbers of sample points were used.

The investigations were performed on CMM Mistral Standard 070705 equipped with Renishaw TP20 probe with the stylus 20 mm length and a ball tip 2 mm in diameter.

## 2. SUBJECT, SCOPE AND METHODOLOGY OF EXPERIMENT

### 2.1. Characteristics of form errors of the measured profiles

The investigations were carried out on cylindrical surfaces at constant value of coordinate $Z$, thus in practice, reduced to 2D circles. The substitute circles were determined using the LSC method. In the first step a precise characteristics i.e. determination of the values and nature of geometry errors of the measured profiles was performed.

The first cylinder of the cross-section roundness deviation $\Delta = 11 \ \mu m$ had a profile presented in Fig. 2 (standard deviation of profile $s = 1,52 \ \mu m$) and the spectral structure of the profile shown in Fig. 3. There is no dominance of any harmonic component in the spectrum, which indicates a lack of the systematic form error. It can be assumed that the errors were of quasi-random distribution.

![Fig. 2. Roundness profile of the first circle](image)

Rys. 2. Odchyliki okrągłości pierwszego profilu
Fig. 3. Spectral structure of the first profile
Rys. 3. Analiza widmowa pierwszego zarysu

Fig. 4. Roundness profile of the second circle
Rys. 4. Odchylki okrągłości drugiego profilu

Fig. 5. Spectral structure of the second profile
Rys. 5. Analiza widmowa drugiego zarysu
The roundness deviation of the second cylinder was nearly the same i.e. $\Delta = 12 \mu m$ (standard deviation of profile $s = 1,38 \mu m$) but the shape deviations were completely different in nature. The analysis of the diagrams presented in Figures 4 and 5 shows the presence of a three-lobed error.

2.2. Measurement strategy

The origin of the part coordinate system was defined in the centre of the substitute circle consisting of 1024 sample points, $X,Y,Z$ axes aligned along the machine coordinate system.

The investigations were concerned with the impact of the surface form errors on the fitting uncertainty. This is closely related to the number and distribution of sample points on the surface. For these reason the investigations were carried out for various (3, 4, 5, 6, 7, 8, 9, 10, 12, 15, 18, 24) number of sample points uniformly distributed on the circle. 36 repeats were made for each number of sample points. To eliminate the influence of points locations each set of points was rotated together with the part coordinate system about the origin by angle $10^\circ$ with respect to the proceeding one.

Making use of the strategy described above measurements were performed on the circles shown in section 2.1.

In engineering practice we often face a necessity of measuring on arc defined by a certain angle and radius e.g. a round edge. Owing to the above an attempt was made to find a solution to the following problem: what is the influence of the value of an arc angle on the uncertainty of determining of the arc’s centre position and radius? To find a solution some investigations were made on a given angle. The measurements were focused on a circular sector whose subsequent angles were as follows: $45^\circ, 60^\circ, 75^\circ, 90^\circ, 120^\circ, 180^\circ$. The number of sample points was constant and amounted to twelve. As in the case above the coordinate system was then rotated about the origin by angle $15^\circ$ with respect to the machine coordinate system.

3. RESULTS AND DISCUSSION

In this section the results of standard uncertainties evaluations in $X$ and $Y$ directions of the circle center positions and the standard uncertainties of the estimated diameters as well as the standard uncertainties of the arc radius of circular sectors.

Fig. 6 shows the uncertainty of the $X$ and $Y$ centre position coordinates dependencies: $ux1, uy1$ – random profile and $ux2, uy2$ – determined profile, versus number of sample points.
In the case of the first profile the uncertainties decrease starting from about 1 μm for 3 sample points up to about 0,4 μm for 8 sample points and stay on the same level when the number of sample points is increased.

![Graph](image1)

**Fig. 6. Uncertainty of circle centre coordinates versus number of sample points**

Rys. 6. Zależność niepewności wyznaczania współrzędnych środka okręgu od liczby punktów pomiarowych

In the case of three-lobed circle the standard uncertainties of the centre coordinates assume the highest values for 4 sample points i.e. about 1,5 μm and then decrease rapidly to assume a constant value below 0,4 μm when the sample size becomes larger than 9.

Fig. 7 presents the curves of standard uncertainties variables for the estimation of circle diameters $ud_1$ and $ud_2$.

![Graph](image2)

**Fig. 7. Uncertainty of circle diameter versus number of sample points**

Rys. 7. Zależność niepewności wyznaczania średnicy okręgu od liczby punktów pomiarowych
The diagrams clearly illustrate the dependence between the uncertainty values and surface form errors for a small number of sample points, for 3–7 points $ud_2$ value is twice higher than $ud_1$. From 10 sample points the uncertainty values tend to be similar and assume the values below 0.5 μm.

As a result it can be stated that above 9 sample points, disregarding the nature of surface geometry errors, the uncertainty assumes a constant value for both the circle centre coordinates and the diameter and is lower than the uncertainty of CMM.

Figures 7 and 8 show the results of the uncertainties dependencies on the arc angle for 12 sample points.

Rys. 8. Zależność niepewności wyznaczania współrzędnych środka łuku od kąta łuku

Rys. 9. Zależność niepewności wyznaczania promienia od kąta łuku
The assessment uncertainty of the circle using a portion of the circle of three-lobed error is four times higher than for a circle of random form error for small angles; $Sx^2$ and $Sy^2$ for $45^\circ$ assume the values of several micrometers. This becomes even more evident on the diagram showing the uncertainties of radius determination for both $Sr1$ and $Sr2$. All the uncertainties assume acceptable values only above $180^\circ$.

4. CONCLUSIONS

In the paper the influence of surface geometric errors on the fitting uncertainties of substitute circles using LSM was investigated. The experimental investigations aimed at their practical application in engineering. The analysis of the results made it possible to state the following:

– surface form errors have a significant impact on fitting uncertainty. For a small number of sample points the fitting uncertainty of the substitute feature is several times higher in the case of profiles of systematic form errors than for random profiles,

– for profiles of systematic errors the uncertainty value changes in an abrupt way for a small number of measurement points. Fitting uncertainty, however, tends to decrease with an increase of the number of sample points in both cases,

– there is a certain measurement point number limit beyond which the fitting uncertainty value drops below the uncertainty of the CMM. This number is equal to nine for both types of profiles, i.e. systematic error and random profiles. Thus, it is possible to make a practical recommendation to use over nine sample points when performing measurements on the circular elements of typical machine parts,

– the uncertainty determined for the whole circle by using a randomly chosen arc section is considerably much higher than the uncertainty of the profile determined on the basis of the full circle (for the same number of measurement points). Here the critical value is the arc defined by $180^\circ$ above which the uncertainty values approach the ones determined by the measurement of the point lying on the whole circumference of the circle.

REFERENCES


BADANIE WPŁYWU BŁĘDÓW GEOMETRYCZNYCH POWIERZCHNI NA NIEPEWNOŚĆ DOPASOWANIA W POMIARACH WSPÓŁRZĘDNOŚCIOWYCH

Słowa kluczowe: pomiary współrzędnościowe, element zastępczy, błędy kształtu, niepewność