acta mechanica et automatica, vol.4 no.4 (2010)

INFLUENCE OF COORDINATE MEASUREMENT PARAMETERS ON A FREE-FORM SURFACE INSPECTION RESULTS

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Abstract: Coordinate measurements are the source of digital data in the form of coordinates of the measurement points of a discrete distribution on the measured surface. The local geometric deviations of free-form surfaces are determined (at each point) as normal deviations of these points from the nominal surface (the CAD model). Obtaining discrete data is inseparably connected with losing information on the surface properties. In contact measurements, the ball tip functions as a mechanical-geometric filter. The results of coordinate measurements of geometric deviations depend not only on the grid size but also on the ball tip diameter. This article presents foundations of the influence of the ball tip diameter and the grid size on coordinate measurement results along with the experimental results of measurement of a free-form milled surface in order to determine its local geometric deviations.

1. INTRODUCTION

The issue whether a product meets the appropriate construction requirements is of fundamental importance in producing machine parts. For inspecting the accuracy of parts which consist of geometric shapes such as planes, circles, or cylinders, widely known measurement techniques are used in industry. The accuracy inspection of parts containing free surfaces requires the coordinate measurement method to be applied.

The coordinate measurement technique consists in determining the coordinate values of measurement points located on the surface of an object. As a result of the measurement, a set of discrete data is obtained in the form of the coordinates of the measurement points. The dimensional/form accuracy inspection of free-form surfaces consists in digitalizing the workpiece under research (coordinate measurement with the scanning method), followed by comparing the obtained coordinates of the measurement points with the CAD design (model). The values of local geometric deviations of the free-form surface, or normal deviations of measurement points from the nominal surface, may be calculated by previously determining the deviation components in the *X*, *Y*, *Z* directions (Werner and Poniatowska, 2006; Cho and Seo, 2002). Software of coordinate measurement machines (CMMs) automatically performs such calculation for each measurement point in the *UV* scanning option designed for scanning on the basis of the CAD model (*UV* – directions of the B-spline surface parameterization).

Measurements of real surfaces produce only their approximate views. The approximation degree depends on the accuracy of the applied measuring method. Among numerous factors which have influence on the accuracy, connected with the tool instrument and the measurement environment, there are factors which can be rationally adjusted – such measurement parameters as the sampling (discretization) interval and the diameter of the measuring tip. Both these factors have a strictly specific impact on the measurement results (Adamczak, 2008).

Different sampling strategies (number and location of measurement points) provide different measurement results for the same surface. This is connected to the fact that measuring a finite number of discrete points on the measured surface is actually described by an infinite number of points. Since geometric deviations are different at each point, measurement results depend on the number and location of these points (Badar et al., 2008; Ainsworth et al., 2000). Elkott et al. (2002) proposed to sample points from free-form surfaces based on the surface NURBS features. However, in the majority of cases, measurements are carried out along a regular *u* x *v* grid with the use of *UV* scanning options, which are inbuilt in CMM software. Information on the surface is provided by data of a discrete character. Obtaining such data is inseparably connected with losing information on the surface properties. Planning an effective sampling scheme requires decisions on determining the range of active area and the size of the measurement points grid. The active research, area as well as the grid size determine the measurement results. Geometric deviations of a surface may be decomposed into three components: form deviations, waviness, and roughness. The components differ in respect of lengths of their elementary irregularities (waves). In contact measurements, the ball tip functions as a mechanical-geometric filter (Adamczak, 2008; Dong et al., 1996). The scope of information included in measurement data depends on the ball tip diameter. Therefore, results of coordinate measurements of geometric deviations of free-form surfaces depend not only on the active area and the grid size but also on the diameter of the ball tip end.

In measuring geometric surface textures (form deviations, waviness and roughness) of regular shapes, specialized stylus measurement instruments are used – profilers, roundness measuring machines, form recording instruments, etc. For the particular types of deviations, guidelines for selecting measurement parameters including the tip radius, sampling lengths and assessment lengths, the sampling interval (the number of measurement points), as well as rules of digital roughness filtration have been developed and incorporated in standards. In standards pertaining to measuring straightness and roundness, the recommended maximum tip radii were worked out according to the principle stating that the tip radius is comparable to the boundary wavelength (the filter passing limit), while the distance between measurement points was established according to the principle holding that the number of measurement points in a segment whose length is equal to that of the boundary wavelength, amounts to 7 (Adamczak, 2008). However, there are no strict standards which would unambiguously determine what boundary length of the elementary (harmonic) wave should be adopted for waviness/form deviations, what the sampling interval should amount to, or which tip radius should be used in a specific measurement. No unambiguous criteria exist as to categorizing deviations as waviness or form deviations. Numerous literature sources relating to measuring surface roughness include analyses of the influence of tip geometry and radii on measurement results. In Poon and Bhushan (1995) showed that increasing the tip size leads to the profile deformation, and in effect to decreasing values of the height parameters. Many problems are also connected with selecting the sampling interval. If it is too small, excess data are available, data are strongly correlated, and the surface is represented by a vast number of measurement points. If, on the other hand, the sampling interval is too big, information on the surface properties is lost (the phenomenon of aliasing occurs). It is suggested that selecting the sampling interval should be made according to the tip radius size (Pawlus, 2004, 2007). The boundary length of the measured roughness depends on which parameter, the tip size or the sampling interval, is bigger (Dong et al., 1996; Szabatin, 2003). In measuring form deviations, measurement parameters are not as significant as in measuring surface roughness, although their influence on the measurement results cannot be neglected.

This article presents foundations of the influence of the ball tip diameter and the grid size on measurement results along with the experimental results of measurement of a free-form milled surface in order to determine its local geometric deviations.

2. APPROPRIATE SAMPLING PARAMETERS

The surface image obtained as a result of contact measurements depends to a great extent on the shape and size of the stylus tip, as well as on the number of measurement points (the sampling interval and strategy). Ball-tip ends are mainly recommended. The sampling parameters listed above determine the least boundary length of elementary irregularities represented in measurement data. The parameter which has a decisive influence is the one which causes a longer wave to be passed. Literature sources suggest different principles of selecting the appropriate tip radius in relation to the sampling interval, most often in the ratios of ½ :1, 1:1 and 2:1 (Adamczak, 2008; Dong et al., 1996; Pawlus, 2007).

Contact measurements take into consideration deviations of specific wavelengths which have not been filtered by the ball tip because the ball tip functions as a mechanical-geometric low-pass filter. Thus, the scope of information included in measurement data depends on the ball tip diameter. In coordinate measurements, ball-tip styluses are used, and styluses with ball tips of d = 1, 1.5, 2, 3, and 4 mm in diameter are produced. The nature of a ball tip functioning in the character of a mechanical-geometric filter is illustrated in Fig. 1.

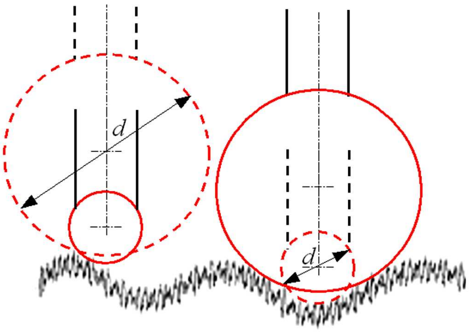

Fig. 1. The nature of a ball tip functioning in the character of a mechanical-geometric filter

In measurement planning, the choice of the d diameter of the ball tip should be made first, according to the measurement purpose and the range of information required on the characteristics of the measured surface. Defining the influence of the ball tip diameter/radius as a mechanical filter, i.e. unambiguously determining the filtration boundary, is difficult, especially in the case of changing-curvature surfaces. Adopting to measurement the principle suggested in the literature sources pertaining to measuring roundness deviations [4], which states that the boundary wave length is comparable to the tip radius value, means that in the case of using a stylus tip of d = 1 mm in diameter, irregularities of the length values greater than 0.5 mm is passed; in the case of the stylus tip of d = 2 mm in diameter, irregularities of the length values greater than 1 mm is passed, etc.

The second important factor which influences measurement results is the sampling interval, in the case of scanning a free-form surface with a CMM along a regular u x v grid, which is directly connected to the number of measurement points. For measurements with the use of machines with contact probes, the number of points is a serious limitation. In choosing the sampling interval T, the principle used in tests on measurement signals, derived from the Nyquist theory, states that a continuous signal may be reconstructed from a discrete one if the former was sampled with a frequency at least twice as big as the spectrum limit frequency should be taken into account (Szabatin, 2003)).

The knowledge of the principle mentioned above makes it easier to make decisions on the length of the sampling interval while planning coordinate measurement strategies. This particular measurement parameter also results in a mechanical-geometric filtration. According to the theorem quoted above, adopting the interval value of 1 mm means that the obtained measurement data contain information of elementary surface irregularities of more than 2 mm in length.

Adopting the cited in literature (Pawlus, 2007) principles to selecting parameters of contact measurement at the same time, *d:T* equal to 2:1, choosing a ball of e.g. 2 mm in diameter, and the 1 mm sampling interval, the boundary length of elementary irregularities represented in measurement data amounts to 2 mm. Since there is not any unambiguous criterion for categorizing unevenness as waviness or form deviations, while presenting measurement results, it is difficult to specify what these results represent. In deciding on the ball tip diameter and the size of the measurement grid, it is advisable to focus on the purpose of measurement and to include detailed information concerning the measurement parameters in measurement reports.

3. EXPERIMENTAL INVESTIGATIONS

The experiments were performed on a free-form surface of a workpiece made of aluminium alloy with the base measuring 100 x 100 mm (Fig. 2), obtained in a three-stage milling process using in the last stage a ball-end mill of 6 mm in diameter, rotational speed equal to 7500 rev/min, working feed 300 mm/min and zig-zag cutting path in the *XY* plane. The measurements were carried out on a Global Performance Brown&Sharpe CMM (PC-DMIS software, MPE_E = 1.5+L/333 μm), equipped with a Renishaw SM25 scanning probe, a 20 mm stylus with a ball tips of 2 and 4 mm in diameter. Scanning of the whole surface was performed for two different combinations of the measurement parameters, the tip end diameter, and the sampling interval (the number of measurement points), observing the rule of selecting *d:T* equal to 2:1. All the measurements were repeated three times; the tables and plots present mean values of the obtained results.

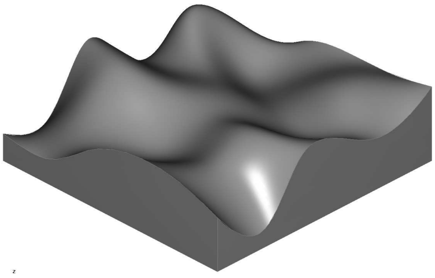

Fig. 2. The CAD model of the surface

In the first stage, the surface was scanned (without applying probe radius compensation), with the use of a ball end tip of 2 mm in diameter with the *UV* scanning option (the option built in PC-DMIS software), 10 000 uniformly distributed measurement points were scanned from the surface (100 rows and 100 columns, sampling grid 0.01*u* x 0.01*v*), and the process of fitting the data to the nominal surface was then carried out in which the least square method was applied and all the measurement points were used. The location deviation was minimized in this way. The measurement process was subsequently repeated, and ε local geometric deviations were computed. The obtained measurement data are presented in a graphical form. Figure 6 shows a spatial plot of the ε local deviations with reference to the *x* and *y* nominal coordinates.

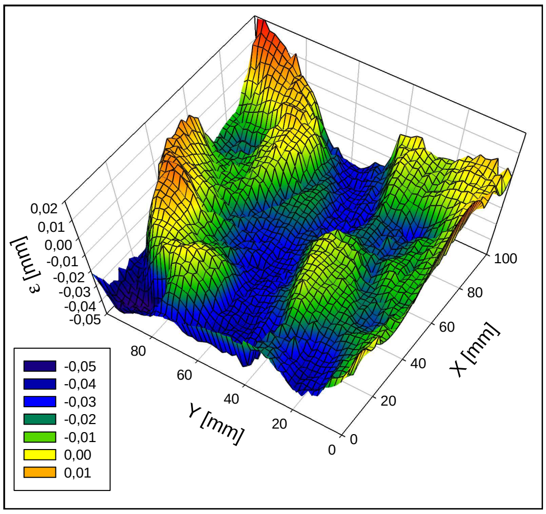

Fig. 3. Spatial plot of geometric deviations versus *XY* plane

In the subsequent stage, the measurements were carried out with the use of a ball end tip of *d* = 4 mm in diameter, and 2500 uniformly distributed measurement points (50 rows and 50 columns, sampling grid 0.02*u* x 0.02*v*) were scanned. The experiment results are compiled in Fig. 4 as well as in Tab. 1.

Tab. 1. Statistical parameters of ε local geometric deviation sets, with the whole surface scanned

Number of meas. pts.	10000	2500
Sampling grid	0.01*u*x0.01*v*	0.02*u*x0.02*v*
Sampling interval *T* [mm]	~ 1 mm	~ 2 mm
Tip diameter *d* [mm]	2	4
Std. deviation [mm]	0.011	0.009
Mean [mm]	-0.017	-0.015
Minimum ε [mm]	-0.049	-0.036
Maximum ε [mm]	+0.019	+0.013
Form/waviness dev. [mm]	0. 068	0.049

In both the cases, the principle of selecting *d:T* – 2:1 was applied. According to the principles described in Section 2, measurement data obtained in measurements performed with the tip end of *d* = 2 mm in diameter and the sampling interval of *T* = ~ 1 mm, include information on surface irregularities whose lengths exceed 2 mm. In the second case, for the tip end of *d* = 4 mm in diameter and the sampling interval *T* = ~ 2 mm, data include information on cases of wavelength longer than 4 mm.

As it had been expected, the form deviation value for the tip end of *d* = 4 mm and *T* = ~ 2 mm was smaller than that for *d* = 2 mm and *T* = ~ 1 mm (Tab. 1). The tip end of the bigger diameter did not reach points located in the irregularities indentations less than 4 mm length; additionally, some cases of irregularities on prominences were omitted because of a bigger sampling interval. Consequently, the mean plane is located higher, and the minimum value is bigger than in the case of a smaller diameter and a smaller sampling interval (Fig. 4, Tab. 1). In order to facilitate comparison of the deviation maps, the plots in Fig. 4 were made using the same scale for the ε deviations axis. Comparing the maps, a bigger area of negative deviations can be observed in the case of measurements with the tip end of $d = 2$ mm (Fig. 4a). As a result of applying different measurement strategies, significantly different results were obtained. The observed surface form/waviness deviations differed by approx. 0.02 mm, which constitutes approx. 1/3 of their values.

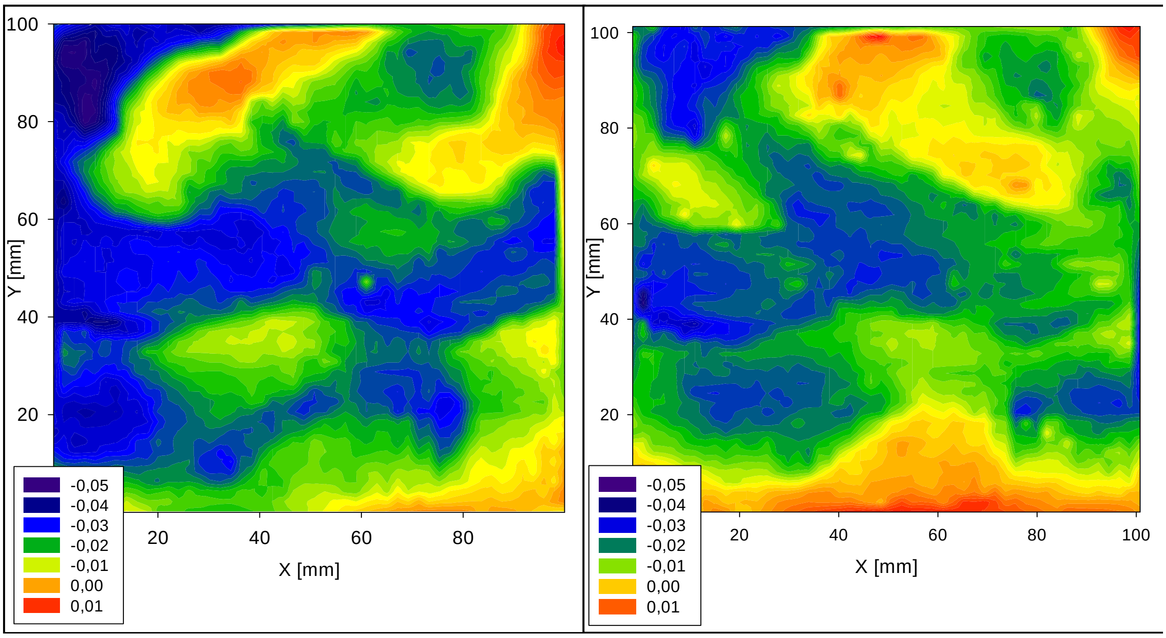

Fig. 4. Maps of geometric deviations versus *XY* plane, *a)* $d = 2$ mm and 10000 points, *b)* $d = 4$ mm and 2500 points

4. CONCLUSIONS

The article brings up the problem of selecting parameters in measuring geometric deviations of free-form surfaces, performed with the use of CMMs with contact probes. Such parameters as the tip end diameter and sampling interval determine contact measurement results because the parameters cause geometric-mechanical filtration. The parameter which determines passing longer waves exerts a decisive influence. The principles of selecting parameters, suggested in literature sources, were summed up. Two different parameter combinations were applied, observing the rule of the ratio of the ball end diameter to the sampling interval equal to 2:1. In the first measurement, the tip end amounted to $d = 2$ mm, and the sampling interval to $T = \sim 1$ mm; in the second one, the values were 4 mm and 2 mm respectively. The obtained measurement results differed to a great extent. In the case of the bigger diameter and the bigger sampling interval, cases of elementary irregularities of the lengths less than 4 mm were filtered mechanically, and the observed form/waviness deviation was smaller by 1/3 than when the parameters had smaller values.

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The work is supported by Polish Ministry of Science and Higher Education under the research project No. W/WM/13/2010