Journal of Machine Engineering, 2018, Vol. 18, No. 3, 78–86
ISSN 1895-7595 (Print) ISSN 2391-8071 (Online)

Received: *13 January 2018* / Accepted: *14 August 2018* / Published online: *28 September 2017*

accuracy, coordinate measuring systems,
probing systems

Piotr GASKA[1*]
Maciej GRUZA[1], Wiktor HARMATYS[1]
Adam GASKA[1], Jerzy SLADEK[1]

METHOD FOR PREDICTING THE ACCURACY OF ROTATIONAL ELEMENTS MEASUREMENTS USING THE FIVE-AXIS COORDINATE MEASURING SYSTEM

The measurements of solids of revolution are one of the most common task in industrial practice. Therefore it is not surprising, that new solutions dedicated to improve accuracy and acceleration of measurements of rotational components are emerging. In this group, the new generation of articulating probing systems (with ability of continuous indexation) is worth mentioning. These probing devices combined with standard CMM forms the five-axis coordinate system. Such solution results in measurements acceleration and also improve measurement repeatability. Studies on this type of probing systems proved that their accuracy depends strongly on the angular orientation of probing system used during measurement. Therefore authors developed model that allows simulation of probing system errors for any orientation. This article describes an attempt to use the model to find the configuration of the probing system that would provide the highest accuracy for rotational elements measurements. The simulation results are compared to the real measurements of standard elements performed on five axis measuring system. Described prediction method could have a beneficial effect on improving the accuracy of measurements and, as a result, on reducing production costs by minimizing the risk of erroneous decision on the conformity of products with their geometric specifications.

1. INTRODUCTION

One of the most important demands formulated by the industry is the reduction of the quality control duration what would contribute to acceleration of the manufacturing process. To fulfil this requirement new measuring methods are developed and the acclaimed ones are improved. This trend could be easily observed also in the field of Coordinate Measuring Technique. Systems like Structured-light 3D scanners or CMMs equipped with contactless probing system allow to measure thousands of points on the surface of measured object and compere measured points coordinates with CAD model. To this moment the biggest drawback of such methods is their mediocre accuracy. At the same time the tactile methods are improved. One of the latest solution is a new generation of articulated heads used in so-called five-axis measuring systems, which allow to perform

---

[1] Laboratory of Coordinate Metrology, Cracow University of Technology, Cracow, Poland
[*] E-mail: piotr.gaska@pk.edu.pl
https//doi.org/10.5604/01.3001.0012.4618

measurements using rotational movements of head with limited influence of machine's kinematics. Such probing system can be oriented freely within their working range, and what is more important, their orientation can be changed during measurement. The Coordinate Measuring Machine equipped with this kind of probing system become a redundant system because the same point in measuring machine volume can be achieved with almost infinitive mutual configurations of machine and probing system. Therefore the issue of choosing such orientation of measured workpiece and probing system that will ensure the highest possible accuracy become even more important than in case of classical CMMs. In relation to CMMs with standard probing system with a rigid orientation, the five-axis measuring systems significantly shortens the duration of rotary element measurements, because in such measuring tasks the head movements are mainly used during the measurement. In the case of machines with a rigid structure, made of heavy materials, application of discussed probing systems may reduce the duration of rotational features measurement even by half [1]. Measurements of solid of revolution are one of the basic measurement tasks performed in industrial and laboratory practice, many elements from the automotive, aviation and machine industries can be included in this group of spatial objects. Considering the information given above authors decide to develop the method for predicting the accuracy of rotational elements measurements using the five-axis coordinate measuring system. This article describes the subsequent steps of prediction system development and its verification.

2. PROBING SYSTEMS USED IN FIVE-AXIS MEASURING SYSTEMS

The crucial element of five-axis measuring system is articulating probing system with ability of continuous indexation. Such probing systems can be divided into two groups: the touch-trigger and measuring probing systems. In both cases the kinematic structure of the articulated probing system is the same but the way of detecting contact between the stylus tip and the measured surface is quite different. The first mentioned group utilizes well known solution in which the probing system is a electromechanical switch that generates an impulse when contact occurs. Touch-trigger articulating probing systems in fact consist of two detachable elements (according to manufacturer specifications): touch-trigger probe and head which is responsible for changing probing system's orientation. The articulating probing system can rotate about orthogonal axes (Fig. 1). Rotation about vertical axis (marked as *B*) is unlimited while rotation around the horizontal axis (marked as *A*) is possible in the range from –115° to 115°. The probing system is oriented vertically when *A* value equals to 0°.

The angular position is determined with angular encoders, wherein final coordinates of measured points are calculated using encoders readouts and indications of linear scales. In case of measuring probes contact detection is realized differently. The styli used in this solution are hollow inside to allow the laser beam to travel from light emitter to reflector attached to stylus tip. Reflected beam is split and directed to photodetector responsible for sensing the deflection of probing system which is considered during determination of coordinates of measured point.

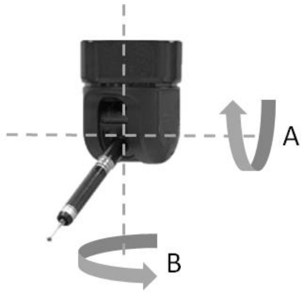


Fig. 1. The articulated probing system used in five-axis systems with marked axes of revolution *A* and *B*

The accuracy of five-axis measuring system depends on number of factors including errors typical for standard CMM like geometrical errors, position threshold, metrological drift, etc. The errors specific for five-axis measuring systems are related with articulating probing system. The factors affecting such probing systems include: geometrical calibration of head and qualification of probe (according to manufacturer nomenclature), probing system hysteresis, length of stylus used during measurements, algorithms used for measured features calculation etc. Research undertaken at Laboratory of Coordinate Metrology showed that one of the most important factors influencing measurement accuracy of five-axis measuring systems is angular position of head which was used during coordinates acquisition. Undertaken experiments proves that results obtained for the same measuring task may vary up to several micrometres depending on used probing system orientation. It should be also noted that on the contrary to the classic CMMs in case of five axis measuring system realization of one measuring task is often done using several, sometimes very different probing system orientations.

The probing process is complex phenomenon and can be divided into four main stages: approach of stylus tip with constant speed to the measuring surface, stylus tip contact with measuring surface, identification of contact point position, retract from measured surface [2]. Ideally, the coordinates of probing points indicated by the machine should be the same as the actual point of stylus tip contact with measuring surface. The difference between these coordinates can be regarded as a total error of the probing system [2]. This fact is caused by number of factors, which can be divide into two main groups of contributors: the interactions between stylus tip surface and the measured object surface and the factors connected with probing system operation principle. The two main approaches to probing system errors determination can by find in literature [2-4]. In first approach the probing system is tested separately from CMM on specially prepared experimental set-ups [3, 5]. Such methods gives deep insight into the probing system performance as the CMM errors are not present during experiments, but information obtained using these methods cannot be easily transferred to real measurement when probing system is part of whole measuring system. The second approach is based on the measurements of material standards [2, 3, 6]. The reference object that could be used in this method must met following requirements: 1) the size of used standard has to be small enough to minimize the influence of kinematic errors on experiment results (usually the diameter of standard should be within the range between 10 mm and 30 mm); 2) the reference object should be characterized by small form errors regarding the accuracy of tested probing system (form errors should not exceed 0.2×*PFTU* defined according to [7]). If both mentioned conditions are fulfilled it is assumed that the errors present during measurements can be attributed to the probing system. Basing on described method in order to describe the accuracy of probing systems, the conception of Probe Error Function (*PEF*) was developed at LCM [2, 6] which links the probing system error with approach direction on the measured point.

The most important disadvantage of the methodology based on the measurements of reference object is the fact that influence of CMM will be always present in the experiment results. However because the five axis measuring system can perform measurements using only rotational moves of probing system, mentioned drawback can be omitted, therefore the *PEF* was used at LCM to model the accuracy of probing systems used in five axis measuring systems. The model is based on experimentally gathered results. The test procedure involves measurements of standard ring with different orientations of probing system which can be described using appropriate values of A and B angles. However because the certain probing system orientation can be achieved with the limitless number of approach directions the third parameter is used to give the information about approach vector utilized during measurement. Then the *PEF* can be written in following form:

$$PEF = PE(\alpha, A, B)$$

where: α – angle in which probing system is working, A – the angle around the horizontal axis of probing system, B – the angle around the vertical axis of probing system, PE – probing error.

For all measuring points in each of chosen standard ring positions, the mean values of PEF and the standard deviation are calculated. Then the scaled and shifted t-distributions is assigned to each point, with parameters (x, s, v), where x is the mean radial *PE*, s is the standard deviation associated to x and v is the number of degrees of freedom equalled to number of measurements minus one. The positions included in experiments constitutes the reference grid which is used to determine *PE* value for given model input parameters. The simulation is based on the Monte Carlo method which uses probability density functions and trilinear interpolation adapted for usage in polar systems.

3. EXPERIMENT AND RESULTS

All measurements described in this paper were performed on the Zeiss WMM850S CMM, located in the air-conditioned room at LCM. During whole experiment the ambient conditions were monitored and the temperature in room varied between 19.4°C – 20.8°C, however object temperature was monitored separately and machine temperature compensation was active during measurements. The machine measuring volume is 800\1200\700 mm. During the measurements the machine was equipped with Renishaw PH20, with touch trigger TP20 probe. The Fig. 2 presents the experiment set-up. Firstly the preliminary experiments were performed in order to gather the input data set for model.

The 25 mm reference ring was attached to steel block, which was installed in swivel and tilting vise which allows to change the ring orientation in machine measuring volume. As there are countless number of possible orientations of probing system firstly the appropriate number of standard positions have to be chosen. The greater number of the positions allows to model the probing system errors more accurately but it extends the time needed for experiments.

Fig. 2. The experiment setup. Zeiss WMM850S equipped with Renishaw PH20 probing system and reference rings

The interpolation method used in the model requires regular distribution of standard positions that will constitute the reference grid. In that case the working range of both angles used by probing system must be divided into equal intervals. If the interval for *A* would be set as 10° and interval for *B* angle set as 30° that would give the number of 162 positions in which the reference object should be measured, at least 10 times for each position. It would take a few days to carry out such measurements. Authors decided to choose such number of positions that can be measured within few hours because methodology that need the several days of implementation experiments would have little chance of interest from users of five-axis measuring systems especially those working in industry. The 24 orientation of the ring was chosen which can be defined using the *A* and *B* angles. The *A* angle changes at 30° in range between 0° and 90°, while the *B* changes at 60° in range between –120° and 180°. During model preparation the ring was measured using only rotational movements of probing system in 64 points, and the best fitted circle was calculated. Then in each point the radial error was determined. Measurements were repeated 10 times and for each measuring point the mean value of error and standard deviation were calculated. The mean value is treated as systematic part of error, standard deviation describes random part. The Fig. 3 presents the results obtained using developed model.

In next step the model was used to simulate the circularity measurement results for orientations covering the working range of the probing system. The iteration step for *A* angle was set as 15° and for *B* angle as 5°. For each position circularity measurement was simulated using developed model and on the basis of 1000 simulations the uncertainty was determined according to [8]. In next step the three positions characterized by the smallest uncertainty were found together with three positions in which the determined uncertainty have the biggest values. Then for these six position the uncertainty was determined experimentally using the calibrated workpiece method [2, 9]. Consecutive steps of experiment are presented schematically in Fig. 4.

Calibrated workpiece method uses multiple measurement of calibrated reference object of the shape and size similar to the measured object. The essence of the method is the omission of the causes of measurement errors for their impact in the global form. The ring of 20 mm was chosen as the measured object, and the 34 mm ring was used as a reference. Both were measured with the same strategy, the 16 measured points were distributed evenly in the middle of the rings height. During measurement only rotational movements of probing system were used. The measured object and reference ring were measured 10 times in each position. The results of experiment are shown in Table 1 and in Fig. 5.

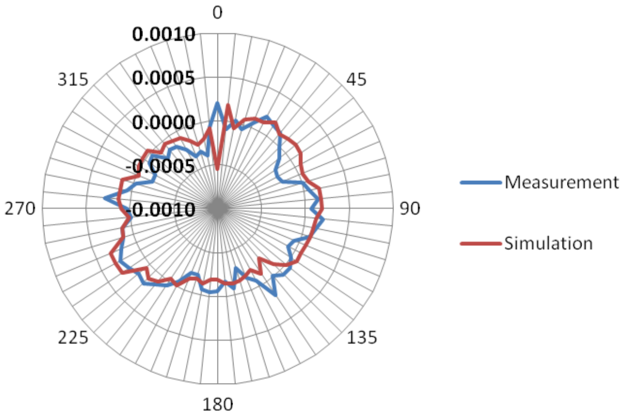


Fig. 3. The comparison of radial errors for ring measurement obtained using developed model and through the measurements for ring set in position in which its axis was parallel to stylus orientation *A* 45° *B* -45°, radial error values (in mm) in dependence of α (in°)

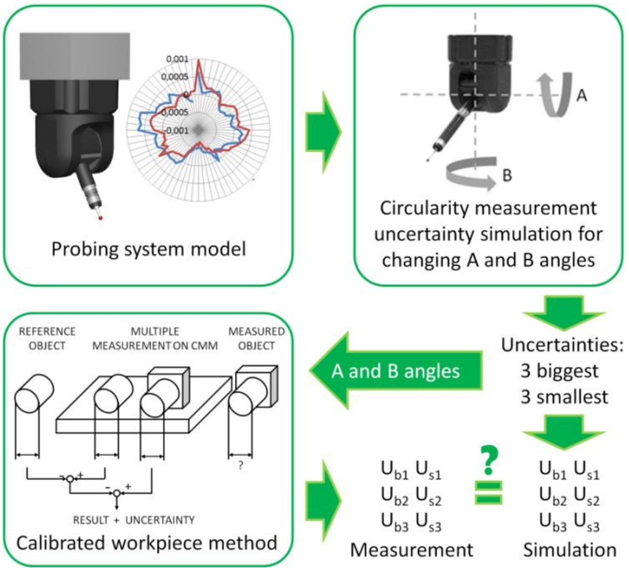
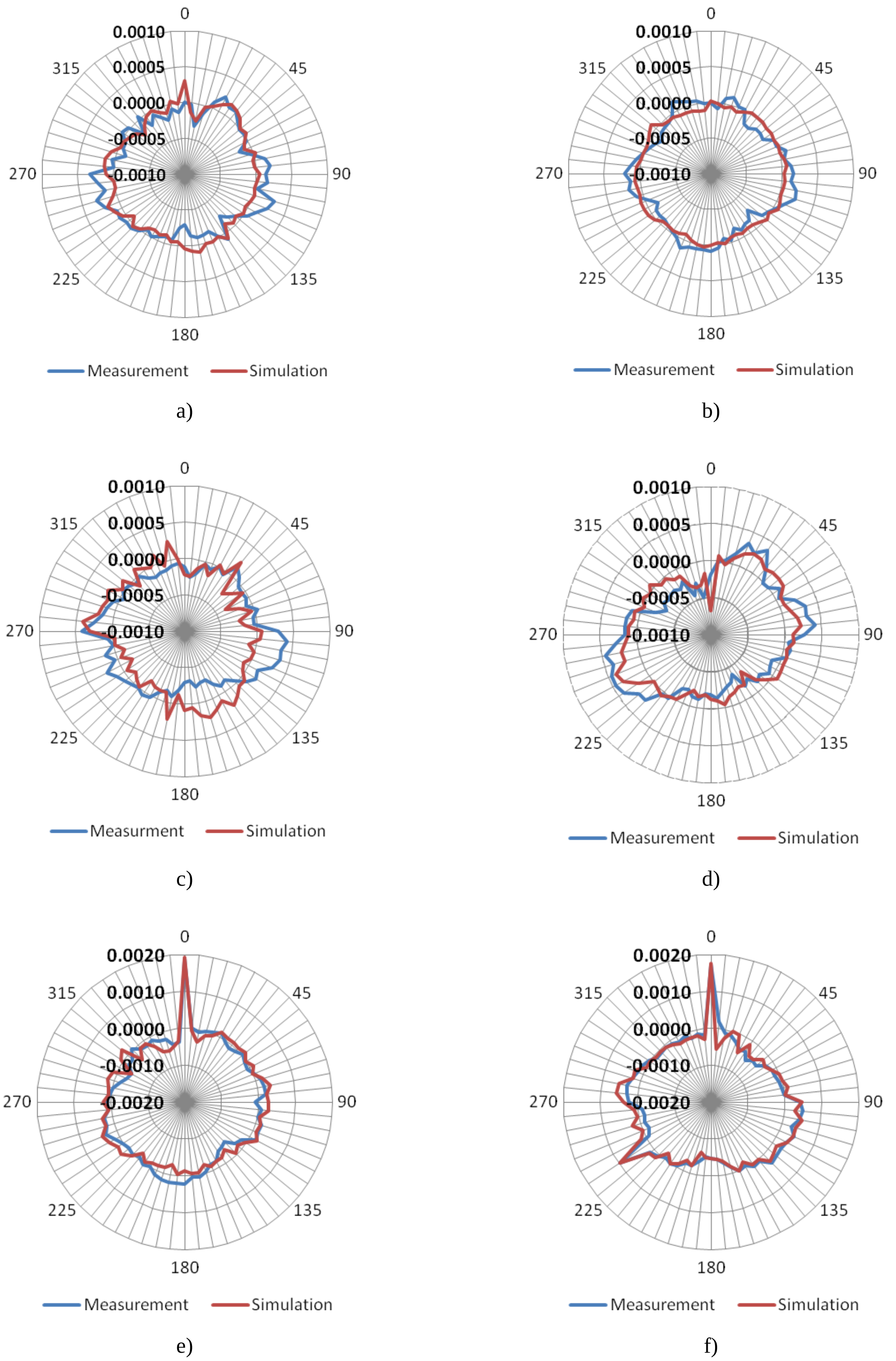


Fig. 4. The scheme presenting consecutive steps of experiment



a) b) c) d) e) f)

Fig. 5. Comparison of results obtained experimentally and by simulation for different orientations of probing system (*A* and *B* in °), radial error values (in mm) in dependence of *α* (in °):
a) *A* = 15, B = -15, b) *A* = 75, *B* = -165, c) *A* = 15, *B* = 60, d) *A* = 45, *B* = -120, e) *A* = 75, *B* = -120, f) *A* = 60, *B* = 75

Table 1. The determined uncertainty of circularity measurement obtained from experiment and by simulation, and the difference between them segregated ascending in terms of uncertainty obtained for calibrated workpiece method. Presented values represents three positions characterized by the smallest uncertainty and three positions in which the determined uncertainty have the biggest values. All values are given in mm

Position of ring	Calibrated workpiece method	Simulation method	Difference
A 15, *B* -15	0.0005	0.0003	0.0002
A 75, *B* -165	0.0006	0.0005	0.0001
A 15, *B* 60	0.0007	0.0005	0.0002
A 45, *B* -120	0.0019	0.0014	0.0005
A 75, *B* -120	0.0021	0.0015	0.0006
A 60, *B* 75	0.0043	0.0036	0.0007

4. CONCLUSIONS

Analysing the results of the conducted research, it can be concluded that the developed model shows high compliance with the results obtained using a metrologically validated uncertainty estimation method. Authors believe that the method for predicting the accuracy of measurements presented in the article, may be useful for the preparation of a measuring strategy for rotating elements inspection. Differences between the values obtained experimentally and by means of simulation that equal to 0.0001 or 0.0002 mm have reached the level of repeatability of the machine. Relatively worse results were achieved for positions in which the higher uncertainty values were estimated using calibrated workpiece methods. This phenomenon can be explained by varying influence of correction of systematic error in calibrated workpiece method as it requires comparison with standard for each position. This problem requires further research, including identification of kinematic errors of probing system to formulate unambiguous conclusions.

The results obtained for the calibrated workpiece method shows that five-axis coordinate systems are characterized by high variability of uncertainty depending on the used angular orientation of the probing system. It can be noticed that for some orientation of the probing system, even slight change in configuration, causes a significant difference in measurement uncertainty. Change in the *B* angle from -165 to -120 for the same value of *A*, cause increase of uncertainty of the measurement by 1.5 µm, while the highest observed difference between the positions included in the experiment reached over 3 µm. Therefore it can be pointed out that utilization of the accuracy prediction method can significantly contribute to improving the accuracy of measurements carried out with the use of five-axis coordinate systems.

As the direction of further research authors indicate the development of the model so it would allow to predict the accuracy of the measurement utilizing both the rotational movements of the probing system and the translational moves of the machine.

ACKNOWLEDGEMENTS

Reported research were realized within confines of project financed by the Polish Ministry of Science and Higher Education topic no.: M-10/447/2017/DS-M.

REFERENCES

[1] GRUZA M., GĄSKA A., GĄSKA P., HARMATYS W., SŁADEK J., 2016, *Analysis of impact of the working mode on the accuracy of the five-axis measuring system*, Mechanik, 11, 1708–1709, (in Polish).

[2] SŁADEK J., 2016, *Coordinate Metrology - Accuracy of Systems and Measurements*, Springer Verlag GmbH.

[3] RATAJCZYK E., WOŹNIAK A., 2016, *Coordinate measuring systems*, Oficyna Wydawnicza Politechniki Warszawskiej, (in Polish).

[4] WECKENMANN A., ESTLER T., PEGGS G., MCMURTRY D., 2004, *Probing Systems in Dimensional Metrology*, CIRP Annals-Manufacturing Technology, 53/2, 657–684.

[5] DOBOSZ M., WOŹNIAK A., 2005, *CMM touch trigger probes testing using a reference axis*, Precision Engineering, 29, 281–289.

[6] SŁADEK J., GĄSKA A., *Modelling of the Coordinate Measuring Systems Accuracy*, Journal of Machine Engineering, 16/3, 34–46.

[7] ISO 10360-5:2010 – Geometrical product specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) – Part 5: CMMs using single and multiple stylus contacting probing systems.

[8] Supplement 1 to the "Guide to the expression of uncertainty in measurement" – Propagation of distributions using a Monte Carlo method, JCGM 101:2008.

[9] ISO 15530-3:2011 – Geometrical product specifications (GPS) – Coordinate measuring machines (CMM): technique for determining the uncertainty of measurement – Part 3: use of calibrated workpieces or measurement standards.