

Coordinate measurement of complicated parameters like roundness, cylindricity, gear teeth or free-form surface

Prof. Dr.-Eng. J.Chajda, Dr.-Eng. M.Grzelka, MSc.-Eng. B.Gapinski, MSc.-Eng. M. Pawłowski,
MSc.-Eng. M.Szelewski, Dr.-Eng. M. Rucki

Division of Metrology and Measuring Systems
Institute of Mechanical Technology
Poznan University of Technology, Poznan (Poland)

Abstract: In the paper, the problems of the complicated parameters measurement with Coordinate Measuring Technique have been discussed. CMM is often used for the measurement of such parameters as roundness or cylindricity. However, the accuracy of such a measurement is dependent on measurement strategy including number of probing points, model of form deviation and fitting element. The investigations had led to the creation of software aiding the operator's decisive process. The program has been presented and the test results have been discussed. Other program, aiding the measurement of gears with assumed accuracy, has been presented, too. Moreover, the free-form surface measurement has been pointed out, together with the problems of the accuracy analysis of CAD transformations.

Keywords: Coordinate measurement, roundness, cylindricity, gears, free-form surface

Introduction

In the modern industry Coordinate Machine is a basic technique of measurement. It is universal, fast and accurate device, applicable for various measurement tasks. Apart of typical length measurements, it is able to measure complicated details and parameters like roundness, cylindricity or free-form surface, as well as such elements as a gear teeth. However, in case of complicated measurement, metrological analysis should be done.

Roundness measurement

One of the most often geometrical elements in produced details are shafts and holes. In most cases they represent very responsible part of the machines, therefore they require very thorough, full analysis of accuracy. It is not enough just to measure their diameters or positions, it is crucial to measure their out-of-roundness as well.

The measurement of this kind of form deviations may be performed using both universal and specialized measuring devices, dependent on the assumed uncertainty, price and time of the measurement. Fig. 1 presents one of the possible classifications of the roundness measurement methods. Fig. 2 shows the schemes of most common non-reference roundness measurement.

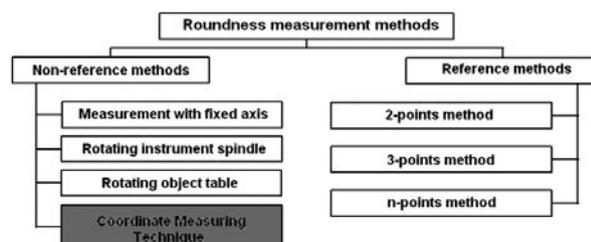


Fig. 1. Methods of roundness measurement [1]

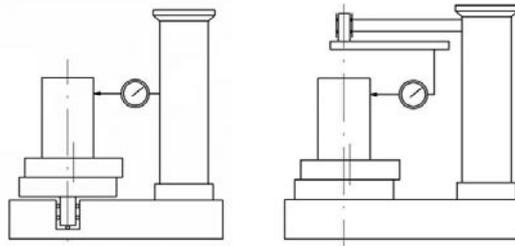


Fig. 2. Non-reference methods of roundness measurement with rotating table (left) and rotating spindle (right) [1]

Specialized devices are accurate and fast, but in most cases only one kind of deviations may be measured with one device. Universal measuring tools may be used for measurement of many geometrical parameters like dimensions, position and form, but they may provide too small accuracy of measurement. Recently, Coordinate Measuring Machines (CMM) became alternative, because they are, on one hand, universal and fast (able to measure with the same tempo as the production runs [2]), and, on the other hand, accurate.

Industrial practice, however, indicates very low metrological knowledge among the CMM operators. Very often the measurement is performed with the minimal points number, which is far from enough to obtain metrologically correct results. Of course, geometrically ideal would be determined by three points only, but in reality any measured detail has form deviation of various values and type. Figures 3 and 4 show why the minimal number of points is not enough and leads to the erroneous result of measurement. The increase of the points number may solve this problem. Our investigation proved that the increase of measuring points number leads to higher accuracy of the results. However, when measuring with touch trigger probe, each additional measuring point requires additional time of measurement.

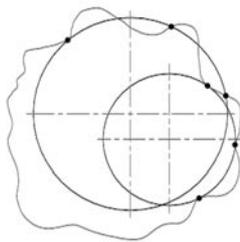


Fig. 3. The measuring results affected by inappropriate measuring strategy

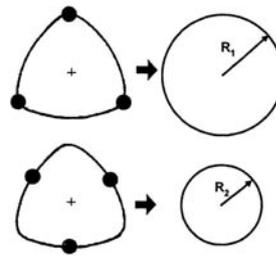


Fig. 4. The radius measurement affected with three-points measurement strategy (when 3-angular detail is measured)

It appears obvious that the number of probing points should be increased. The question is: to which extend? In order to answer this question, the simulation program CYRKIEL for the roundness measurement with CMM has been developed [3]. It was designed to aid the proper preparation of the measurement strategy. The decisive window of the program is shown in the Fig. 5. It is able, among others, to calculate recommended number of points dependent on the dimensional tolerances, circle diameter, model of the form deviation (which is highly dependent on the manufacturing technology of given detail), and the assumed reference circle [4].

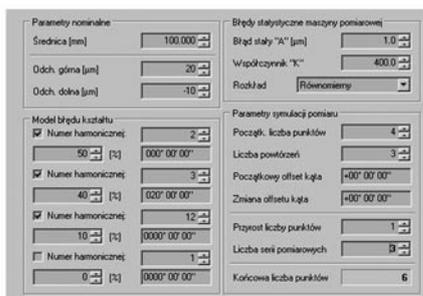


Fig. 5. Decisive window of the CYRKIEL program



Fig. 6. DEA Image Clima 7.7.5 CMM (left) and probing head SP25M (right)

The series of the simulations were performed. The results proved that the minimal number of probing points generate too large dispersion of the measurement results, but in the same time, the increase of points number is effective

only up to certain number. Simulation results underwent verifications with the laboratory measurements. In the experimental researches, the touch trigger probing head SP25M made by Renishaw was applied in the DEA Image Clima 7.7.5 CMM (Fig. 6). In the investigations, four standard fitting methods [5] were applied: LSCI – Least Squares Reference Circle; MZCI – Minimum Zone Reference Circles, MCCI – Minimum Circumscribed Reference Circle and MICI – Maximum Inscribed Reference Circle. The gained results are shown in the Table 1 [6]. They differ for different fitting methods, therefore it must be always taken into consideration before the measurement strategy is chosen. From the functional point of view, the measurement of the shaft/bore elements should be based on the principle of „maximum material”. This way, the shafts should be related to the MCCI fitting elements, while the bores to the MICI elements. Then the information on the circle center point could be gained, and above all on its true diameter influencing the cooperation of the two elements.

Table 1. Recommended number of probing points for certain types of form deviations (measured detail was of diameter 100 mm); X, Y – coordinates of the circle center, D – diameter, RN – roundness deviation

Fitting element	Out-of-roundness type								
	Oval			3-lobing			4-lobing		
	X ; Y	D	RN	X ; Y	D	RN	X ; Y	D	RN
LSCI	12	12	48	8	12	42	10	12	38
MZCI	24	48	48	16	36	42	16	22	38
MICI	24	48	48	16	24	42	20	34	38
MCCI	20	24	36	16	32	32	20	20	28

Cylindricity measurement

In the similar way, problems CMM of cylindricity measurement led to the idea of the expert program VALETZ supporting the operator’s decisions. It consists of following modules:

- **Module generating the errors:** here the CMM’s errors are superposed on the geometrically ideal cylinder (Fig. 7). The errors are generated by inaccuracy of machine’s details and by model of form deviation.



Fig. 7. Module generating the errors

- **Calculation module:** after the errors are generated and superposed on the ideal cylinder, the fitting element is calculated according the chosen approximation criteria. There are four fitting methods in common use, shown in the Fig. 8: Least Square Cylinder (LSCY, also called Gaussian), Minimum Circumscribed Cylinder (MCCY), Maximum Inscribed Cylinder (MICY) and Minimum Zone Cylinder (MZCY, also called the Tschebysheff cylinder).

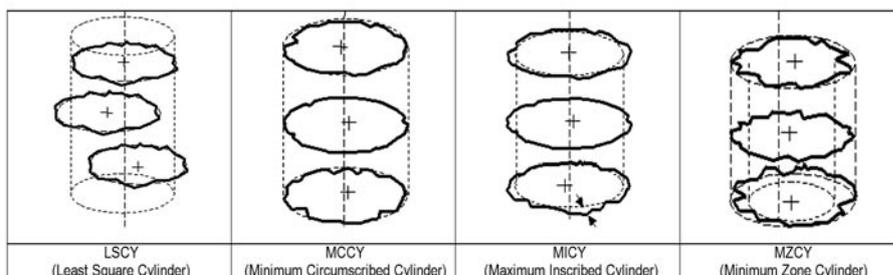


Fig. 8. Approximation criteria

- **Statistical module** enables to generate up to 9999 repetitions of the cylinders with given parameters and deviations, for further analysis. Operator can presume errors according to Gaussian or steady distribution.
- **The results module** is designed for presentation of the analysis results in graphs and in tabs. The record is available in various formats, and could be prepared for following parameters:
 - current intersection,
 - statistics of the intersections in the current shaft,
 - statistics of the intersections in the whole sample,
 - current shaft,
 - statistics of the shafts in the whole sample.
- **Decisive module** based on iteration could find out the minimal number of points and profiles which enable the measurement of given deviation model with given accuracy.

The expert program enables to perform comprehensive metrological analysis of the decisive and measurement process in order to determine errors and their influence on the final measurement result.

During the works on the simulation program VALETZ, the reliability of the algorithms for circle and cylinder calculations was checked. The check contained several tests of virtual model simulations as well as real measurements of the physical detail. In the Table 2 [7], there are examples of the results gained from the simulations and the measurements.

Table 2. Parameters obtained from simulation, CMM measurement, and specialized device

Number of probing points per intersection	Parameter	Program Valetz simulation [μm]	CMM DEA measurement	
			Repeatability test [μm]	Repeatability test with rotation of the coordinate system [μm]
4	Mean value	24.14	10.46	9.13
	Range	6.15	0.55	7.64
	Standard dev.	2.53	0.20	3.13
8	Mean value	36.65	38.22	31.63
	Range	1.45	0.90	4.61
	Standard dev.	0.55	0.39	1.98
16	Mean value	37.05	36.96	37.33
	Range	1.52	1.31	4.40
	Standard dev.	0.66	0.57	1.56
32	Mean value	38.28	38.16	38.08
	Range	1.38	1.06	0.69
	Standard dev.	0.53	0.42	0.26
64	Mean value	38.90	39.08	38.86
	Range	1.15	1.04	1.47
	Standard dev.	0.42	0.43	0.58
		Measurement with the specialized device PIK-2 [μm]		
	Mean value		38.67	
	Range		1.24	
	Standard dev.		0.23	

The performed simulations and the measurements led to the conclusion that the expert program gives the results of simulations very close to the results of the measurement with Coordinate Measuring Machines and ones obtained from specialized device. Only in cases of 4 and 8 points per intersection, the relative error of the method exceeded the assumed value of 10 %. In other cases, the error was less than 10 %. The differences between the simulation results and the experimental measurement are small. It proves that the applied calculation algorithms in the program VALETZ are correct.

Simulation software is still under development. It is aimed to be able to work independently and to calculate minimal number of the probing point allowing the correct measurement of cylindricity with Coordinate Measurement machine.

Cmm measurement of the gears

Some producers of the typical universal Coordinate Measuring Machines deliver many additional measuring programs for the special purposes as e.g. programs for the gears' measurement. It is of great importance to carry out the accurate metrological analysis of the measuring process and the final error of the performed measurement of gear with the CMM. The analysis includes:

- analysis of all errors occurring in the measuring process,
- analysis of the influence of particular errors on the measured deviations,
- determination of the relations describing particular errors,
- determination of the uncertainty of the gear accuracy evaluation.

The accuracy of particular deviation of the measured gear may be described by formula:

$$\Delta() = \Delta_{x0,y0} + \Delta_{poz} + \Delta_{kor}, \quad (1)$$

where:

$\Delta()$ – error of particular deviation measurement (i.e. involute profile, basic radius, tooth thickness, pitches, tooth line),

$\Delta_{x0,y0}$ – error of the coordinate system center determination,

Δ_{poz} – error of the positioning of the probe tip during the contact with the measured surface,

Δ_{kor} – error of the correction applied in the algorithm.

Before the measurement with CMM, the coordinate system must be determined. This process introduce its own error affecting all the following measurements. The error of the coordinate system center determination could be described as following:

$$\Delta_{x0,y0} = f(N_{pkt\ pom}, E, \Delta_{kszaltu}), \quad (2)$$

where:

$N_{pkt\ pom}$ – number of the measuring points steadily distributed on the measured circle,

$E(MPE_E; U_3)$ – uncertainty of the CMM defined by standard ISO 10360-2:2000 [8],

$\Delta_{kszaltu}$ – form deviations (ovality and 3-angular lobing as most common and most affecting the accuracy of circle center location determination).

The worked out algorithms, software and metrological analysis of the CMM's gear measurement accuracy is a basis for the complex measurement of the gears. It is possible to determine the ability of CMM to measure gears manufactured in certain accuracy class, as it is shown in the Fig. 9. The algorithm enables also to convert the task and to choose appropriate CMM's accuracy for the particular measuring task.

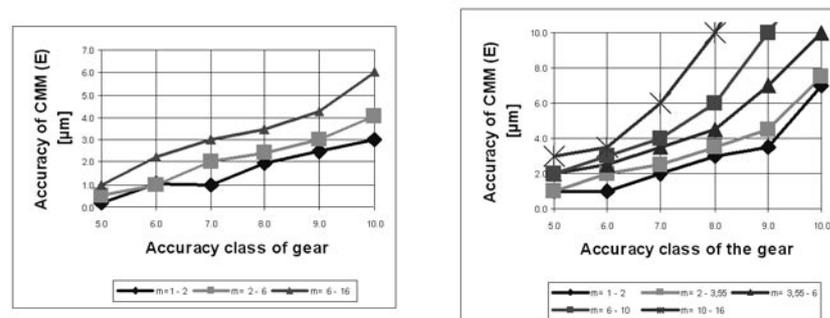


Fig. 9. Accuracy of CMM recommended for the gear measurement according to the criteria 10% of tolerance (left) and 20% of tolerance (right) [9]

Additionally, coordinate measurement may be used in the reverse engineering process. Accuracy of the whole reverse engineering process depends on errors of Coordinate Machine, design process, CAD/CAM system, digitaliza-

tion process, and manufacturing technology. The example of free-form surface digitization is included into the paper.

Free form surface digitization and analysis

The analysis of the free-form surface digitization consisted of simulations and laboratory measurement. The simulation was performed in off-line mode, without CMM, using the CAD model of the free-form surface (Fig. 10, left). In the experimental verification, the CNC controlled coordinate measuring machine equipped with the scanning head and software for the measurement based on CAD model was used. The measured detail with free surface was made out of alloy ALZn 5Mg3Cu (Fig. 10, right). The measurements were performed in the repeatability conditions, in the air-conditioned laboratory by means of the DEA Global machine presented above in the Fig. 6.

Digitization with the CMM is possible using contact and non-contact methods. In contact methods, both touch trigger and scanning, the accuracy is higher, but the time of measurement is longer, especially when the number of probing points is large. Non-contact laser probing heads could shorten the digitization time, but the accuracy of the measuring data is ca. 10 times worse than in contact methods [2]. That means, the operator must answer the question: what is the priority – time or accuracy? Is it true that the larger is the number of measuring points, the higher is the accuracy of CAD reproduction of the surface?

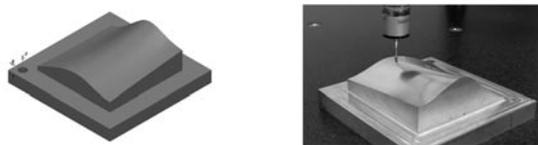


Fig. 10. CAD model of free-form surface (left) and its physical model (right)

The performed investigations were aimed to answer those questions. The analysis consisted of two stages. The first stage consisted of simulations with *off-line* measurement program and CAD model in order to gain knowledge on the problem. The second stage was based on the experimental measurement (on-line measuring program, CMM, material object). In the graph (Fig. 11), besides of the range of deviation scattering, the time of data processing is shown, needed to generate the surface in the CAD system. Of course, this time is not bounding because it depends on the computer ability and the program algorithms, but it represents important trend which must be taken into consideration.

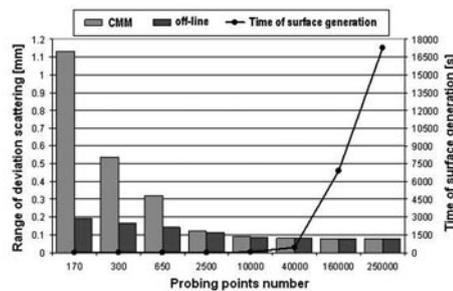


Fig. 11. Deviations of the CAD reproduced surface from the nominal one compared with the generation time dependent on the number of probing points

Conclusions

Coordinate Measuring Machines are the accurate and fast devices able to perform various and complicated measuring tasks. They could be used for the measurement of out-of-roundness parameters, gear profiles, free-form surfaces and other. However, operator should take into consideration many specific factors of the particular measurement task. Otherwise, the achieved results could be not reliable. The metrological analysis and investigations carried out in the Division of Metrology and Measurement Systems (Poznan University of Technology, Poland) enabled to work out the recommendations on a measurement strategy, as well as to prepare the software aiding operators' decisions.

References

1. Adamczak S.: *Odniesieniowe metody pomiaru zarysu okrągłości części maszyn*, Wydawnictwo Politechniki Świętokrzyskiej, Kielce 1998.
2. Ratajczyk E.: *Współrzędnościowa technika pomiarowa*, Warszawa, Oficyna Wydawnicza Politechniki Warszawskiej, 2005.
3. Grzelka M., Pawłowski M., Gapiński B.: Expert Programs Supporting the Form Deviations Measurement; IV. International Congress on Precision Machining ICPM 2007; Sandomierz 25-28.09.2007; ISBN 978-83-88906-916; Vol.1; s. 303-310.
4. Norma PN-ENV ISO 14253-2:2006 Specyfikacje geometrii wyrobów (GPS). Kontrola wyrobów i sprzętu pomiarowego za pomocą pomiarów. Część 2: Przewodnik szacowania niepewności pomiarów w GPS, przy wzorcowaniu sprzętu pomiarowego i kontroli wyrobów; PKN Warszawa 2006.
5. ISO/TS 12181-1:2003: Geometrical Product Specifications (GPS) – Roundness – Part 1: Vocabulary and parameters of roundness; International Organization for Standardization, 2003.
6. Gapiński B.: *The roundness deviation measurement with CMM, Coordinate Measuring Technique – Problems and implementations*. University of Bielsko-Biala 2008, ISBN 978-83-60714-0-9, pp. 279-288
7. Chajda J., Pawłowski M.: *Application Of The Expert Program in the Cylindricity Measurement*, 8th International Conference “Coordinate Measuring Technique”, Ustroń 2008, ISBN 978-83-60714-40-9, pp. 289-300.
8. ISO 10360:2000; Geometrical Product Specification (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM); International Organization for Standardization, 2000.
9. Grzelka M., Gapiński B., Recommendations on the measurement of cylindrical gears with coordinate measuring machines. CD Book of Summaries, XVIII World Congress IMEKO, September 17-22, 2006, Rio de Janeiro.