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THE ACCURACY ANALYSIS OF THE ROUNDNESS MEASUREMENT WITH COORDINATE MEASURING MACHINES

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Abstract: In the article, the form deviation (roundness) measurement with the Coordinate Measuring Machine has been discussed. The influence of the measuring points number and the type of the roundness deviation on the result (since different fitting elements are used) has been presented. The obtained investigation results prove that minimal number of points is not enough for measurement, while the too large number does not improve the measurement, as well. The recommendation on the measuring points number have been given.

Keywords: coordinate measuring technique, roundness.

1. INTRODUCTION

The customers' demands enforce the continual development of the technologies. The shortening of operating time combined with the quality improvement is expected. Thus, the wider metrological analysis is needed, which ensure the complete knowledge on the manufactured product. The measuring devices of higher accuracy should be applied.

One of the solutions is to use specialized devices for particular metrological tasks – e.g. for roundness measurement. However, in such case many specialized devices should be bought. To avoid this, Coordinate Measuring Machine may be applied for many tasks. CMM combines many conflicting characteristics like accuracy and elasticity with high speed of measurement. It may be stated that CMM is able to perform measurement in the same tempo as the manufacturing process runs. The idea of coordinate measurement is to analyze the coordinates of the localized measuring points. Those points are used to determine any geometrical shape of the detail, like point, line, plane, circle, cylinder, and so on. When the diameter of circle is to be calculated mathematically, the coordinates of three measuring points are enough. In metrology, in order to reach higher certainty the minimal points number is four. However, the higher is the number of points, the higher is the "certainty" of the achieved result of measurement. In case of circle, the measured parameters are: diameter (radius), coordinates of the center and the form deviations.

The industrial practice points that pulse measuring heads are used mostly for measurement with minimal recommended number of p oints. In many cases circles are being measured with 4 points, and hardly ever with more than 16 points. The performed investigations proved that it is not enough, especially as the measured detail is to be combined with other one in narrow tolerance [1].

2. THE CALCULATED FITTING ELEMENT IN THE ROUNDNESS MEASUREMENT RESULTS

The results of circle measurement are influented by followith factors: number of measuring points, distribution of points and the chosen fitting element. The standard ISO 6318 gives four fitting elements for circle: Least Square Circle (LSC), Minimal Circumscribed Circle (MCC), Maximal Inscribed Circle (MIC) and the Minimal Zone Circle (MZC) (see fig. 1).

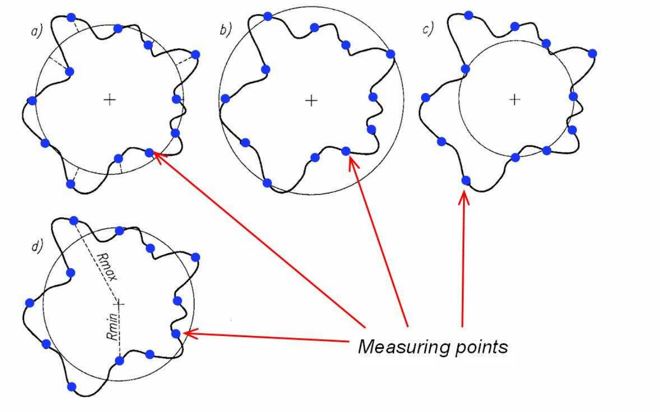


Fig. 1. Fitting elements according ISO 6318: a) Least Square Circle (LSC), b) Minimal Circumscribed Circle (MCC), c) Maximal Inscribed Circle (MIC), d) Minimum Zone Circles (MZC)

Most often as a fitting element is used Least Square circle, which is inappropriate in many cases, especially for moving joints with narrow tolerance. The Gaussian method gives the „mean" shape of the measured detail. When the measured circle is to cooperate in narrow tolerance, the measurement with Minimal Circumscribed Circle (MCC) or Maximal Inscribed Circle (MIC) should be performed.

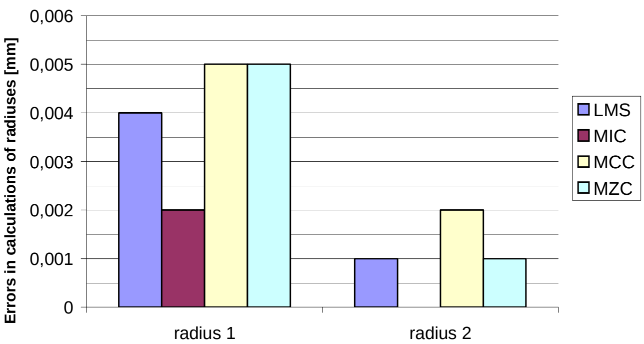


Fig.2. Errors generated by the fitting model

The researches on errors of fitting methods have been performed for several circles placed in the detail [2]. Fig. 2 shows differences between radiuses calculated for the same measuring points, but using different fitting methods. The results differ between one another, and mostly from the correct one.

The software analysis shows that in most cases (up to 90% of measuring tasks) the Gaussian fitting method is used. Surprisingly, this most common fitting method shows the lowest level of correct results – only 8% [2]. Moreover, it is absolutely inappropriate for some measuring tasks. E.g. for obvious reasons, for the shafts MCC method is recommended, and for the openings MIC method. This way the information on the center position is achieved, and above all on actual diameter determining the ability of examined details to be joined and to cooperate.

3. MINIMAL NUMBER OF THE POINTS USED FOR THE MEASUREMENT

The investigations proved that so-called minimal number of points (4) is not enough for the circle measurement. The calculated values of the diameter, position of the center and the form deviation bear large error [1]. The achieved results are influented also by type of the fitting element. In case of ovality of measured circle, 4 measuring points would generate substantially different results dependent on the position of measuring points (fig. 3).

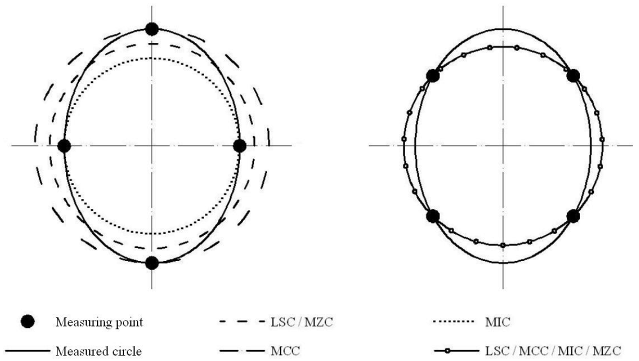


Fig. 3. The results of roundness measurement influented by the distribution of the measuring points and different fitting methods

When the measuring points are placed on the extremal points of the oval, the Maximal Inscribed Circle may be placed in other disadvantageous way. It would be based on 3 points collected by measurement, which would affect the position of the center in one axis (fig. 4).

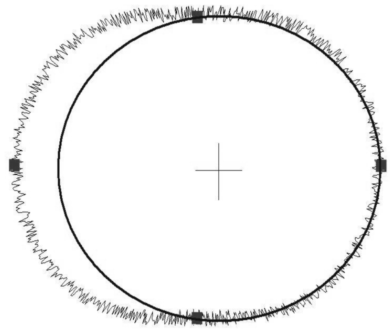


Fig. 4. Measurement of the circle with ovality deviation using 4 points

Additionally, the calculated coordinates of the circle center are affected by the errors of the CMM measurement. Those errors determine the direction of displacement of the calculated center. The value of displacement does not depends on diameter of circle, in depends only on the form deviation value. The larger is the form deviation, the larger is the displacement (fig. 5).

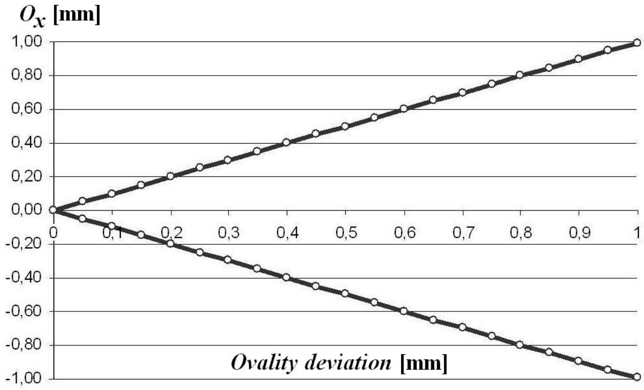


Fig. 5. The circle center location O_x (in x-axis) versus the value of ovality deviation

4. THE INFLUENCE OF THE FITTING ELEMENT AND THE NUMBER OF POINTS ON THE CIRCLE MEASUREMENT RESULTS

In order to increase the effectiveness of Coordinate Measuring Machine, the appropriate strategy of measurement should be worked out. Among others, the number of points should be chosen for particular measurement, dependent on the purpose and parameters (tolerance, form deviations etc.) of the measured detail. Appropriate number of points ensures the achievement of correct results of measurement for known uncertainty of the CMM, with the shortest operation time. The number of measuring points depends on the circle diameter, the form deviation model (determined by the technology of machining) and the assumed fitting element.

The larger is the number of measuring points, the higher is the accuracy of measurement, but pulse measuring heads require more operating time. It is not economically justified, to collect the large number of points with pulse head, because of the operating time and the damage of the measuring head. Each measuring head has certain number of points it is able to collect without troubles. On the other hand, the scanning heads are designed to collect a large number of points. They are alternative for the pulse heads, but they are more expensive and require expensive control software. Thus, the recommendations should be worked out on appropriate number of point for the given form deviation model and fitting element. Also such factors as CMM's accuracy and the tolerance of the measured detail should be taken into consideration, too.

The researches performed in Division of Metrology and Measuring Systems prove that the minimal number of measuring point is absolutely not enough. However, they also show that excessive increase of the measuring points is unnecessary, because further displacement of the circle center, the values of the radius changes and roundness deviations drop under the values of CMM's uncertainty.

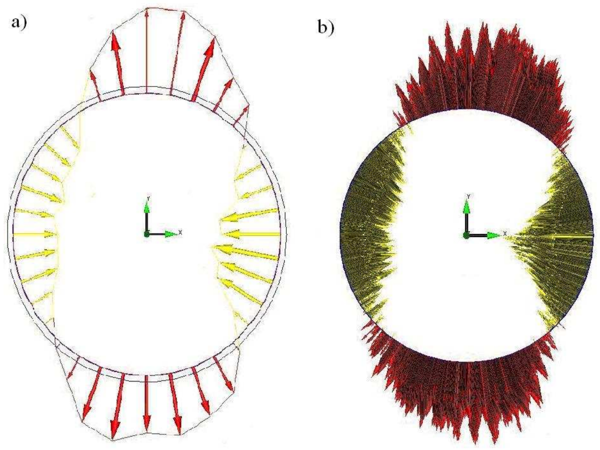
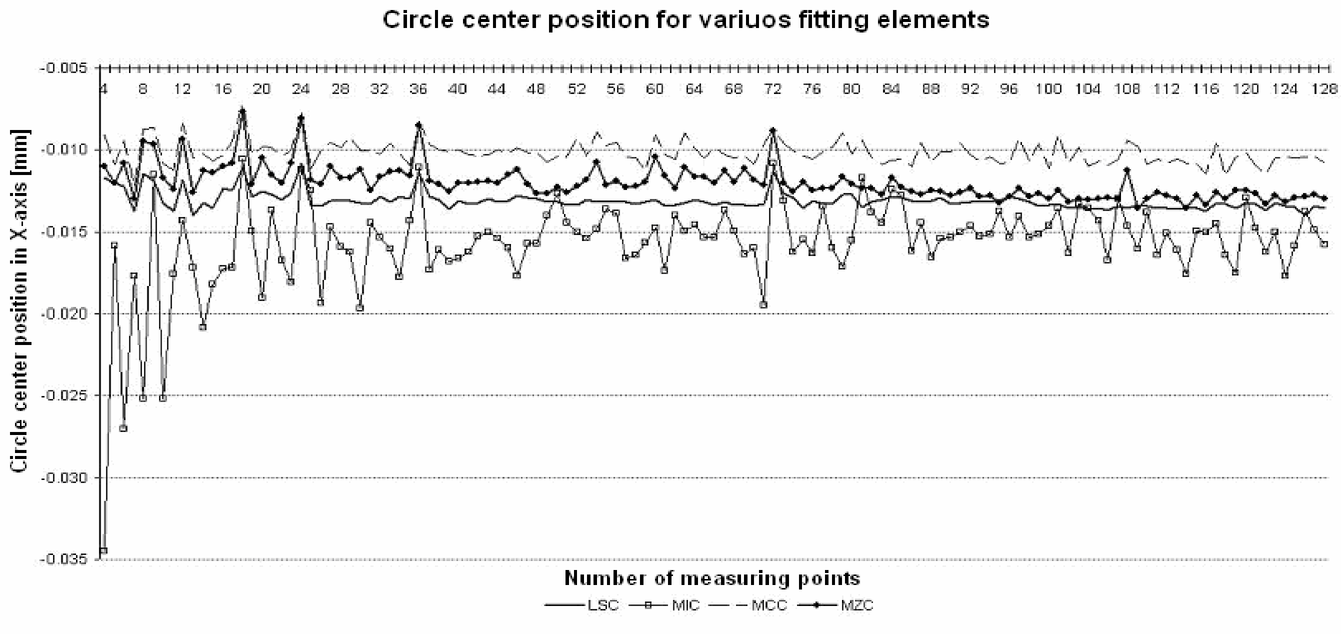


Fig. 6 Graphs of the form deviations:
a) pulse measurement with 36 points; b) scanning measurement with 2992 points (10 points per mm)

Fig. 6 presents the results of measurement of detail



Rys. 7. The influence of measuring points number on the calculated circle center position in X-axis for different fitting elements (WMP - MPE_E = ± (1,5 + L/333) [µm]).

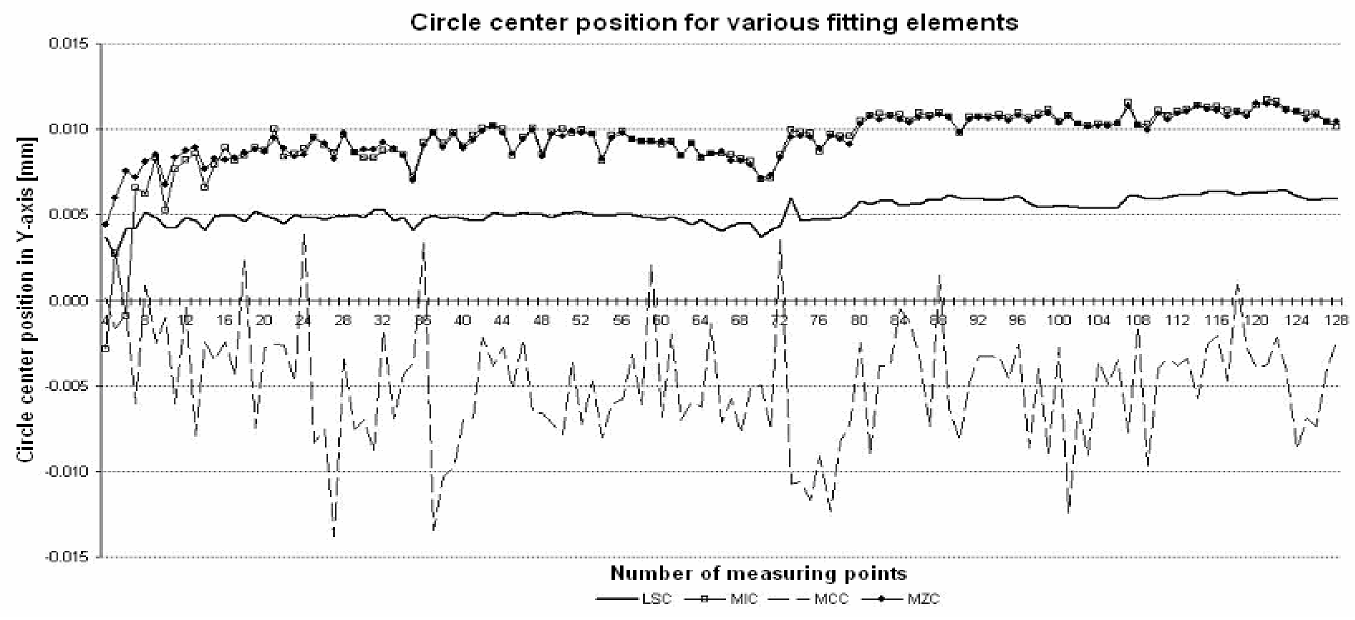


Fig. 8. The influence of measuring points number on the calculated circle center position in Y-axis for different fitting elements (WMP - $MPE_E = \pm (1{,}5 + L/333)$ [µm]).

with form deviation (ovality). The measuremed has been performed with two Coordinate Measuring Machines of uncertainty $MPE_E = \pm (5 + L/200)$ [µm] and $MPE_E = \pm (1{,}5 + L/333)$ [µm]. The achieved results confirmed the previous simulation results. The machines with different uncertainty generate the same character of changes in particular parameters. The difference is only in value of results distribution for different uncertainty. In that case the first stabilization of the circle center position appears for 36 measuring points. The second stabilization appears only after the 72 number is exceeded (fig. 7 and fig. 8).

When the diameter is being measured, the fitting element plays the important role. The results for Least Square Circle (LSC) and Minimal Zone Circle (MZC) give the similar results for any number of points from 4 to 128. The calculated radius value differs in the range of CMM's uncertainty. At the same time, the stabilization of the calculated circle position is reached when the point number is 36 both for Maximal Inscribed Circle and Minimal Circumscribed Circle. The second stabilisation appears also after the number 72 is exceeded (fig. 9).

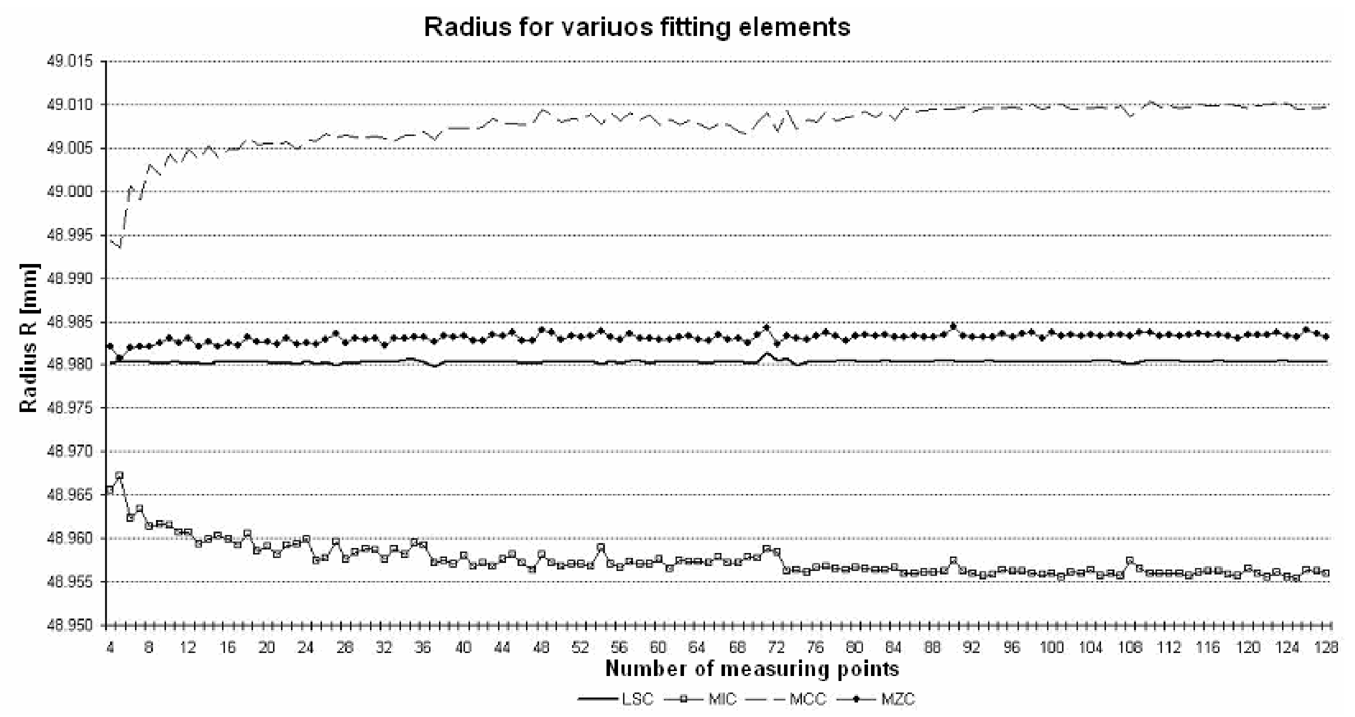


Fig. 9. The influence of measuring points number on radius R for different fitting elements (WMP - $MPE_E = \pm (1{,}5 + L/333)$ [µm]).

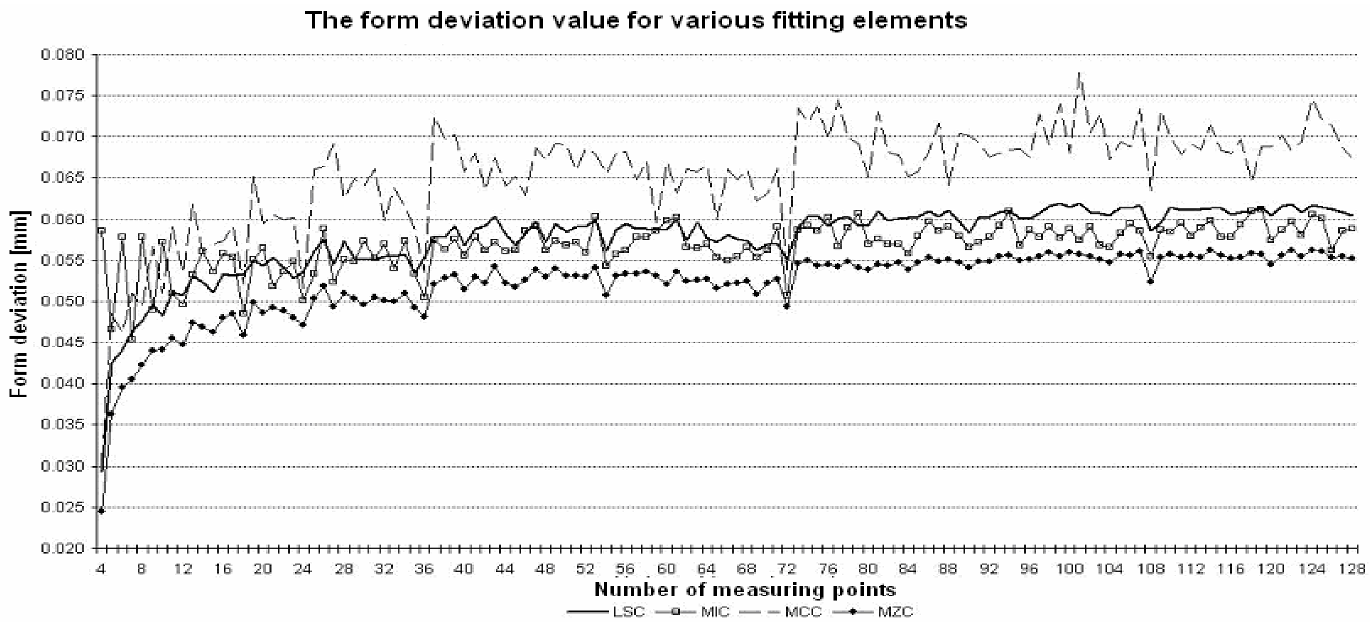


Fig. 10. The influence of measuring points number on form deviation value for different fitting elements (WMP -

Differences between MCC and MIC, as well as LSC and MZC are determined by the fitting element definition itself, while MCC and MIC methods describe the actual form of the detail. It influences the accuracy of the measuring detail evaluation in terms of its functional characteristics. The minimal number of measuring points is not enough for the measurement of the roundness deviation. Like in case of circle center position, stabilization of the achieved value is reached after the number of points exceedes 36. Here also the second stabilization is seen, which appears after the number of points reach 72. Similarly as in case of radius, a small distribution of the results appears for the LSC and MZC models. When the number of points exceeded 72, the distribution would drop to the level of the CMM's uncertainty (fig. 10).

5. CONCLUSIONS

Coordinate Measuring Machines are able to perform the measurement of roundness. In that purpose, both pulse and scanning measuring heads may be applied. The limitation is determinet by the uncertainty of Coordinate Measuring Machine. It should ensure the measurement with accuracy of 10% of tolerance accepted for measured detail. In some extreme situations, these limitations may be widened up to 20% of tolerance.

The researches described above have proved that minimal number of measuring point (for the circle it is 4) is not enough and could generate sufficient differences in results. It has been also proved that functional characteristics of the measured element should be evaluated using models of Minimal Circumscribed Circle for shafts and Maximal Inscribed Circle for orifices (sleeve).

REFERENCES

[1] Nuemann H. J.: "Präzisionsmesstechnik in der Fertigung mit Koordinatenmessgeräten". ISBN 3-8169-2211-2, Renningen 2004.

[2] Swornowski P., Rucki M., "The Errors Occuring in the CMM Fitting Method". Proceedings of the 4th International Conference "MEASUREMENT 2003", Smolenice, Slovak Republic, pp. 316-319.

[3] Grzelka M., Szelewski M.; "Selection of the Coordinate Measuring Machine for the Gear Measurement". Proceedings of the 8th International Symposium on Measurement and Quality Control in Production, Erlangen, Germany 2004, pp. 417-425.

[4] Hemdt A.: "Matematische Grundlagen der Koordinatenmesstechnik". VDI-Bildungswerk, Achen.

[5] Weckennmann A., Eitzert H., Garmer M., Weber H.: "Functionality-oriented evaluation and sampling strategy in coordinate metrology". Precision Engineering 17/4, 1995, pp.244-252.

[6] Adamczak S., Janusiewicz A., Zybała Z.: "Experimental comparison of shape profiles measured with CMM". Vth International Scientific Conference: Coordinate Measuring Technique. Bielsko-Biala 2002, pp.17-22.

[7] Wen-Yuh J., Chien-Hong L., Cha'o-Kuang C.: "The min–max problem for evaluating the form error of a circle". Measurement 26, 1999, pp.273-282.

[8] Dhanish P.B.: "A simple algorithm for evaluation of minimum zone circularity error from coordinate data". International Journal of Machine Tools & Manufacture 42, 2002, pp.1589-1594