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THE INFLUENCE OF FITTING ALGORITHM AND SCANNING SPEED ON ROUNDNESS ERROR FOR 50 mm STANDARD RING MEASUREMENT USING CMM

Coordinate Measuring Machines (CMM) become one of the main requirements in precision engineering for advanced industries, troubleshooting and scientific facilities. CMM data analysis software can contribute significantly to the total measurement errors. The error characteristics in the CMM software are very important from the metrological point of view to find an optimum fitting solution. The final accuracy of a work piece is influenced by many different factors.

In this paper, the fitting software methods and styles touch probe scanning speed factors for three different transverse circles of roundness measurement errors are studied experimentally and discussed in details. The tests have been performed to examine the problem of how to generate reference data sets for cylinder circle measurements. Some error formulae have been postulated to correlate the roundness measurements within application range. These reference data sets are presented to help the CMM designer and operator to get the best fit for roundness measurements.

Keywords: precision engineering, CMM accuracy, fitting methods, roundness errors, probe scan speed

1. INTRODUCTION

Nowadays, it cannot be over-emphasized, the world development is according to ultra-high precision technologies. In both manufacturing and measuring technology an ongoing trend for higher accuracies can be applied. The favor for these technologies is mainly for the engineering metrology. Engineering coordinate metrology is an important branch of quality assurance [1]. Therefore, CMM machines are installed in many of large scale industrial factories, medical laboratories, and scientific research centers, as well as airspace, airplane, and automotive industries. CMM are used to measure the surface quality of machine elements and spare parts of cylinder, piston, gear, and fuel injector nozzles.

Since the required tolerances for manufacturing continuously become smaller, whereas the complexity of work pieces increases, capable measurement techniques have to be applied in order to achieve accurate results with sufficient precision. The final accuracy of a work piece measurement quality is influenced by many different factors [1, 2, 3]. The resultant measurement quality of CMM is limited by deviations and some uncertainties. The measurement deviations in coordinate metrology can be related to the operator performance quality, environmental interaction, work piece finishing, and CMM accuracy. It can be assumed that some influence factors of operator behavior and CMM software accuracy have effective reactions on the measurement quality factors [1].

An error compensation issue of a CMM has been studied related to several factors using different versions of machine software [4, 5]. Earlier researchers have focused on active error compensation of the deterministic error components based on simple models [6-10]. Both of the above error factors have not been studied for their effect on the measurement quality for the same CMM.

In industrial production the true surface can never be known exactly. Therefore, an approximation of the surface is known based on coordinate points using a finite sampling method. The CMM including special software is aimed to detect the geometry of the surface. The CMM fitting software uses the coordinate data to determine a part's location, orientation, form, and deviation of roundness. The fitting algorithms of testing and evaluation for CMM have been in existence since receive a new CMM machine at NIS against a reference algorithm to include a more extensive test program. The advanced **C**oordinate **M**easuring **M**achine model PRISMO Navigation has been delivered to the NIS in Jan. 2006 to offer more accurate measurement services.

In this study, the CMM of fitting software techniques for cylinder roundness measurements, equipped with nine different probe speeds using three detection circles are studied dynamically and discussed in details. The tests have been performed to examine the problem of how to generate reference data sets of measurement strategy for cylinder circle surface at NIS. These reference data sets are presented to get an optimal strategy at dynamic performance for a CMM machine. The objective is to eliminate the repeatable error in turning operations on CMM machines. The goal is to reduce costs according to operation time and improve figure accuracy of visible measurement in a production environment.

Consequently, some CMM error formulae have been postulated to correlate the roundness measurement errors with the probe scanning speed factor for different fitting algorithms within the application range. The objective of the research prepared is to help the CMM operator in developing a methodology for precision assembly as well as error compensation methods to improve the overall system accuracy. This study is very important also for the CMM designer to develop new precision machines.

2. BACKGROUND AND MOTIVATION

In the last few years, the technology of dimensional engineering metrology has been developed specially for large surface instrument manufacturing. In general, industry has been somewhat reluctant to invest in fitting algorithms software. The success of any fitting algorithm application is derived through the abilities of its software fitting performance and characterization. Many of these software systems employ windows-based software to give the CMM user/operator a highly intuitive visual compatibility with logical, menu-driven functions having comprehensive help facilities for operator support.

There are three types of tolerances; they are: the form, position and size tolerance. The form tolerance is the largest possible deviation of an element form. Deviation of work piece form is the value of the deviation of the real form to its nominal design form. Irregularities of surface can be decomposed into form, waviness, and roughness. Waviness is the important variable of the geometric dimension and tolerance in engineering metrology. Waviness includes five different effective parameters; straightness, flatness, roundness, cylindricity and surface profile. Roundness is an essential parameter for any circle and cylinder measurements. To measure roundness, it should include a rotational factor to the measurement, conversely, diametric measurement.

Roundness measuring instruments tend to be using one of two techniques; Talyrond or CMM methodology. Historically in 1954, the rotating pick-up version of the instrument was first made commercially available; this was termed 'Talyrond-1' which developed later. Another way to measure surface roundness is to use a coordinate measuring machine. A standard CMM has three accurate orthogonal axes and is equipped with a touch-trigger probe. The probe is brought into contact with the component being measured at a recorded position. A number of points are taken around the component and these are then combined in computer software to determine the roundness of the component. Typically, the number of data points is very small because of the time taken to collect them. As a result, the accuracy of such measurements is compromised to evaluate the roundness.

2.1. Types of errors

The purpose of CMM software system and operator skill is to determine the final dimensions of the work piece and to provide information about the presented errors in the measurement strategy. Machined surfaces cannot have perfect forms due to various error sources, interaction of machining processes, quality and measurements strategic accuracy. Consequently, in this study, the sources of such surface imperfection or errors will be analyzed to cover two main particular error types. The first error is based on two sub-errors of *form error* and *measurement error*. The *form error* conveys the idea that the work piece has not perfectly the shape of their nominal geometry. Even if the CMM machine were somehow perfect, the point measurements would generally still deviate from the nominally perfect shape. Some form of errors can be expected in many engineering work pieces. The *measurement error* arises when data points are collected on the surface of an object. Sources of error based on CMM adaptation (axial bends in some hardware, probe system imperfections, fixture, etc.), and measurement environment (temperature, vibration, etc.) lead to some inaccuracies in the measured points.

The second main error is called *human error*, since the human interaction is yet another big source of error (sometime even the largest source of error). The *human error* arises when measurement machine operator (metrologist) selects impossible measurement strategy parameters for requirements of an object. Therefore, CMM operator behavior has a significant effect on the measurement errors. These two main types of errors with some others exist in all real-world measurement scenarios. Therefore, the main purpose of the study is projected to the influence of CMM fitting algorithms through nine different probe scanning speeds for three different transverse circle locations of carrying out signals, to:

a. development of the CMM software using closed loop control and to reduce the size of measurement uncertainty.
b. increase operator skills, reduce the operation lost time and cost, to avoid processing mistakes of software strategy applications.

2.2. Fitting Algorithm

The job of the CMM fitting algorithm software is to process the data in such a way that it will be useful to the user. The algorithm testing and evaluation program for Coordinate Measuring Machines has been studied since 1993. There are two main types of circle fitting software algorithms used in CMM called *Gauss* and *Chebyshev* (*Tschebycheff*) [5]. *Karl Friedrich Gauss* (1777–1855) whose renown as the most elegant of mathematicians befits his elegant “least squares” approach attempt to minimize the average error. *Panutij Chebyshev* (1821–1894) with his minimum distance approach addresses the bumps smoothed over by *Gauss’* attempts to minimize the maximum error. Moreover, other new algorithm types of CMM software draw in measurement strategy applications.

3. EXPERIMENTAL WORK

3.1. General

In this work, evaluation of the CMM PRISMO navigator software program through sample carrying out signals has been performed. The evaluation processes include three basic components of the instrumentation system: a data generator, reference algorithm, and a comparator to analyze and interpret the results. The CMM has six fitting categories. The machine software algorithm and probe scanning speed were selected and primary tested in the recommended environmental conditions at NIS laboratory. An eccentric work piece seat base of granite was finely cleaned and located on the CMM test position. The CMM machine was turned on to check the electric power switches and pneumatic pressure, where a styles probe of the long type has been selected and calibrated according to the machine working manual. The performance of the CMM accuracy in scanning measuring mode was verified and accepted within standard specification according to ISO 10360 [11, 12]. An inspection feature consists of one or more surface elements, like a cylinder in this case to find the associated tolerance. In order to determine the accuracy of the approximation fitting algorithm a geometrical model type casing for future tests was created. Many aspects of roundness error measurement strategy have been taken into account according to standard procedures.

3.2. Dynamic Calibration of Stylus System

Dynamic calibration of CMM stylus system is the very important task, especially in the field of study CMM accuracy [12, 13, 14]. The standard measurement methods of both propping error and scanning propping error using reference sphere. The diameter of the reference standard test sphere is required to be between 10 mm and 50 mm with certification for form and diameter. To determine the probing error must probed twenty five recommended points on the reference test sphere surface. To determine the scanning probing error must scan four recommended scanning lines on the surface of test sphere and compute the Gaussian center point of the sphere using all measured points of all four scan lines. Before making measurements with the CMM in the cylinder, the CMM was calibrated using master probe for evaluate standard sphere and using standard sphere for evaluate used probe. The output standard deviation (SD) and CMM test element specification are presented in Table 1.

Table 1. Output data of CMM probes and sphere.

CMM element	Measured radius, mm	SD, mm
Master probe	4.0000	0.0001
Reference sphere	14.9942	0.0001
Used probe	4.0000	0.0001

The CMM has limited specific values of as follows:

$$MPE_E = A + L/K,\ \mu\text{m}.$$

Where MPE_E is the maximum permissible measurement error, A is the constant machine uncertainty equal to 0.9 μm, K is the length constant or slope of line equal to 350, and L is the length measurement in mm.

$$MPE_P = \pm\ 1.00\ \mu\text{m and } MPE_{Tij} = \pm\ 1.90\ \mu\text{m}.$$

Where MPE_P is the maximum permissible probing error and MPE_{Tij} is the maximum permissible error when measuring a part by using scanning mode which called maximum permissible scanning probing error.

3.3. Test Procedure

After CMM adjustment and calibration, a finely finished steel work piece as a ring block has been prepared for the test. The work piece has an outer/inner diameter *82/50 mm*, height of *10.2 mm*, Fig. 1. According to the following plan, measurements have been carried out at three different transverse sections on the work piece inner circles at locations of *4*, *4.25* and *4.5 mm* from the top to detect any roundness error of the surface. The measured sample errors were obtained for nine probe scanning speeds *5*, *10*, *15*, *20*, *25*, *30*, *35*, *40 and 45 mm/s* during *360°* angle range trace of the standard ring respectively. While CMM travelling speed was constant of *15 mm/s* and the number of scan fitting points also was constant with about 1633 ±2 points during measurement tests at temperature condition of $20 \pm 0.5^{o}C$. Each measurement point has 10 times repetitions for the same three transverse circle (x, y, and z) positions.

a) b)

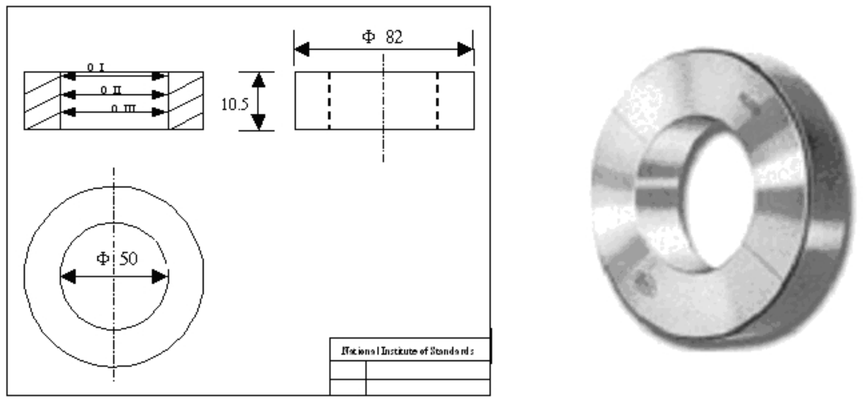

Fig. 1. The tested standard ring block: a. A simple drawing of the cylinder, b. The selected steel ring.

New CMM software has six fitting algorithm types for all measurement applications as follows:

a – Least Square (*Gauss* criterion method), LSQ
b – Minimum Element (*Chebyshev* criterion method), ME
c – Minimum Circumscribed Element (calculation method), MCE
d – Maximum Inscribed Element (calculation method), MIE
e – Inner Tangential Element (calculation method), ITE
i – Outer Tangential Element (calculation method), OTE

Actually, in the roundness measurement application, the ITE fitting technique is equal to MCE technique and OTE fitting technique is equal to MIE technique. Therefore, in the selected three circles, roundness has been determined at each probe scanning speed, where the CMM PRISMO navigator has been selected to the above first four fitting algorithms LSQ, ME, MCE, and MIE only. Determination of roundness measured errors has been included in 1080 experimental measuring tests to differentiate between evaluation qualities of the different measurement strategies.

4. RESULTS PRESENTATION AND DISCUSSION

The PRISOM CMM data fitting using the different ways yields a drastically different resulting geometry. Analyses of roundness error of the four fitting techniques are given in details. However, a question arises which method is suitable to choose and what criterion should be taken at which probe scanning speed. The density of measured points is presented in Figs. 2, 4, 6, 8, 10, 12, 14, 16, and 18. The results obtained are reduced and presented in a more practical and explicit form in Figs. 3, 5, 7, 9, 11, 13, 15, 17, and 19. The roundness error results as functions of the probe scanning speed and fitting technique are given as follows:

4.1. Probe scanning speed 5 mm/s

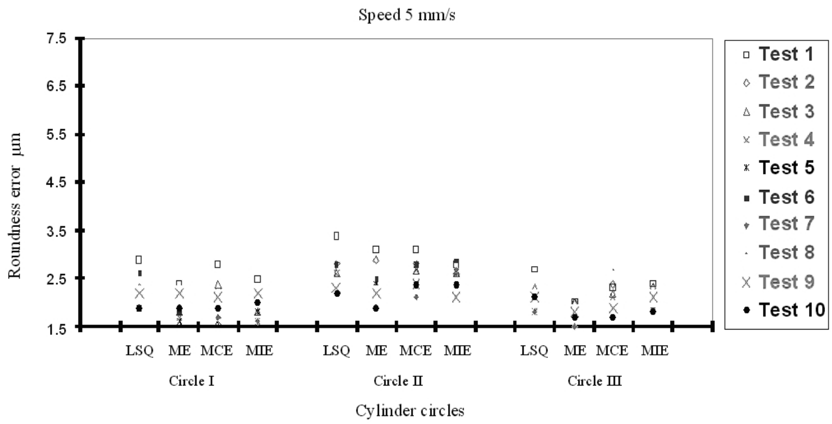

Fig. 2. Roundness errors variation of fitting algorithms for three detection circles at 5 mm/s.

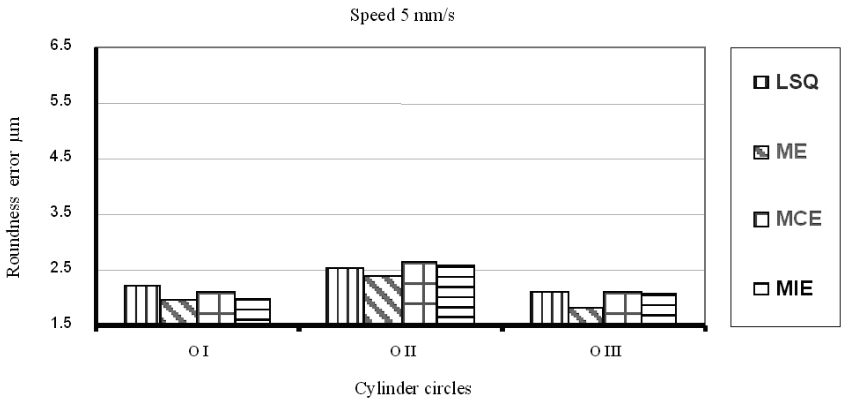

Fig. 3. Measuring errors average of different fitting algorithms at 5 mm/s in the ring circles.

The presentation of 120 test results in Fig. 2 shows the density of measured points for roundness error using different four fitting algorithms of three transverse circles at probe scanning speed of 5 mm/s. Fig. 3 shows the average variation of roundness errors of different types of fitting algorithms for three circle cases I, II, and III. Analysis of the given results indicates that:

- Detection *circle I* measurements have a roundness error range of 0.23 µm from 2.20 to 1.97 µm, while measurements of *circle III* have roundness error limits of 2.11 and 1.81 µm within an error range of 0.30 µm.

- *Circle II* measurements have the highest roundness error 2.65 μm for the MCE fitting method, and the lowest error of 2.38 μm for the ME fitting method. Consequently, *circle II* have the highest roundness error 2.55 μm for the LSQ fitting method.
- According to the application of the fitting technique to all measuring circles, the evaluated error difference between circle measurements as representing values to the fitting method quality, have 0.44 μm of LSQ (2.55 and 2.11 μm) and have 0.41 μm of ME (2.38, 1.97 μm), while MCE (2.65 and 2.1 μm) and MIE have the values 2.59 and 2.01 μm at a maximum difference of 0.55 and 0.58 μm respectively.

4.2. Probe scanning speed 10 mm/s

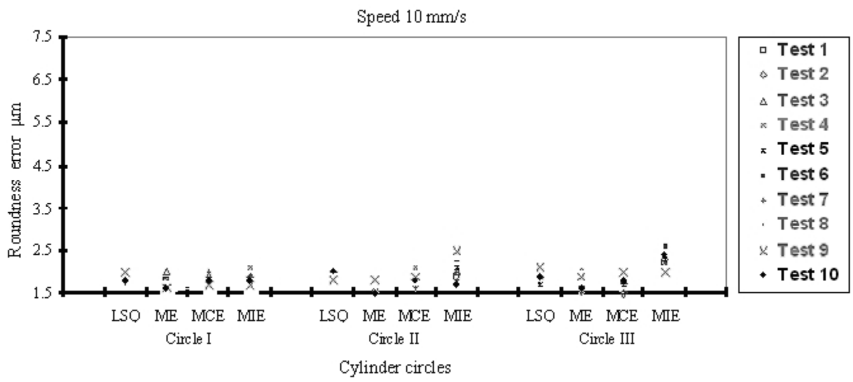

Fig. 4. Measuring errors variation of fitting algorithms for three circles at scanning speed of 5 mm/s.

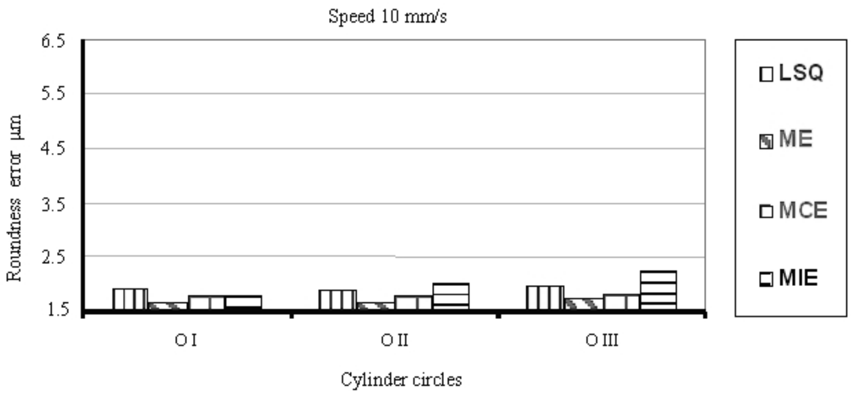

Fig. 5. Roundness errors of fitting algorithms at 10 mm/s for three detection circles.

Figure 4 appears the density of 120 measured tests for roundness error using different four fitting algorithms of three different circles at probe scanning speed of 10 mm/s. Figure 5 shows the variation of roundness errors of different types of fitting algorithms for three circle cases I, II, and III. Analysis of the results indicates that:

- *Circle I* measurements have the highest roundness error 1.93 μm for the LSQ fitting method, and the lowest error of 1.68 μm for the ME fitting method. Consequently, *circle I* has a measuring error range of 0.25 μm.
- Detection *circle II* measurements have a roundness error range of 0.33 μm from 2.01 using MIE fitting method to 1.68 μm using ME fitting method, while measurements of *circle III* have roundness error limits of 2.24 using MIE fitting method and 1.74 μm using ME fitting method within an error range of 0.50 μm.
- According to the application of the fitting technique to all measuring circles, the evaluated error difference between circle measurements as representing values to the fitting method quality, has 0.43 and 0.09 μm for MIE (2.24 and 1.81 μm) and LSQ (1.98 and 1.89 μm), while ME (1.74, 1.68 μm) and MCE have the values 1.83 and 1.80 μm at a minimum difference of 0.06 and 0.03 μm respectively.

4.3. Probe scanning speed 15 mm/s

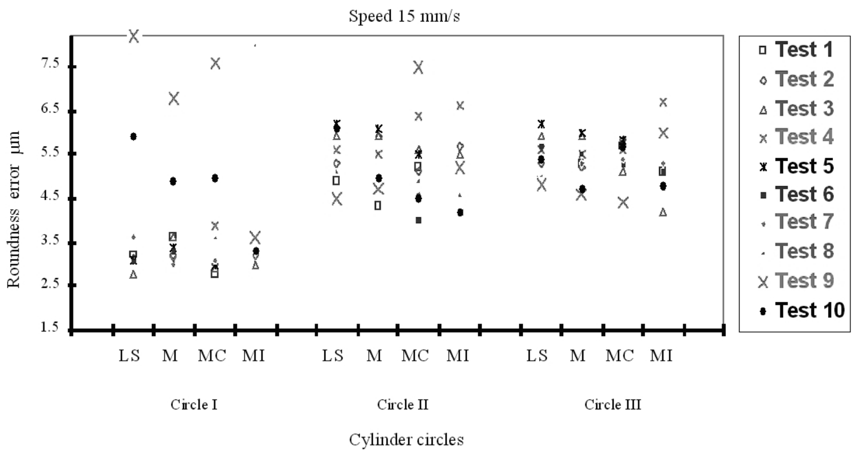

Fig. 6. Measuring errors variation of fitting algorithms for three detection circles at 5 mm/s.

The presentation of results in Fig. 6 shows the density of measured tests for roundness error using different four fitting algorithms of three circles at probe scanning speed of 15 mm/s. Figure 7 shows the variation of roundness errors of different types of fitting algorithms for three circle cases I, II, and III. Analysis of the results indicates that:

- *Circle I* measurements have the lowest roundness error 3.98 μm for the LSQ fitting method, and the lowest error of 3.80 μm for the ME fitting method. Consequently, *circle I* has a measuring error range of 0.18 μm.

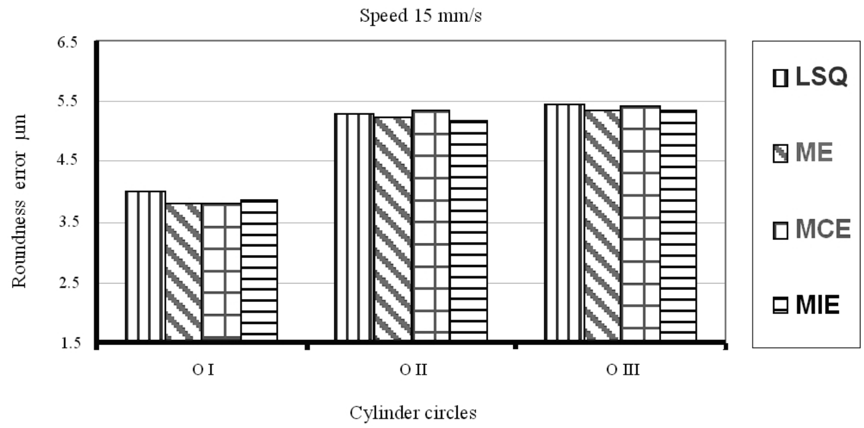

Fig. 7. Roundness errors of fitting algorithms at 15 mm/s for three detection circles.

- Detection *circle II* measurements have a roundness error range of 0.16 µm from 5.33 to 5.17 µm, while measurements of *circle III* have roundness error limits of 5.44 and 5.33 µm within an error range of 0.11 µm.
- According to the application of the fitting technique to measuring circles, the evaluated error difference between circle measurements as representing values to the fitting method quality, has 1.60 and 1.49 µm for MCE (5.40 and 3.80 µm) and MIE (5.33 and 3.84 µm), while LSQ (5.44, 3.98 µm) and ME have the values 5.33 and 3.8 µm at a minimum difference of 1.46 and 1.43 µm respectively.
- The measuring error range has significant variation at 15 mm/s compared to 5 and 10 mm/s testing speed, may be due to probe response at resonance travelling speed.

4.4. Probe scanning speed 20 mm/s

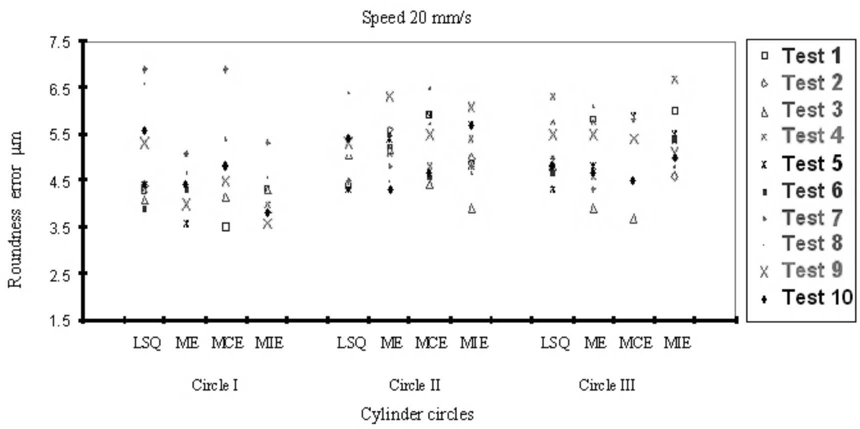

Fig. 8. Roundness errors variation of fitting algorithms for three detection circles at 5 mm/s.

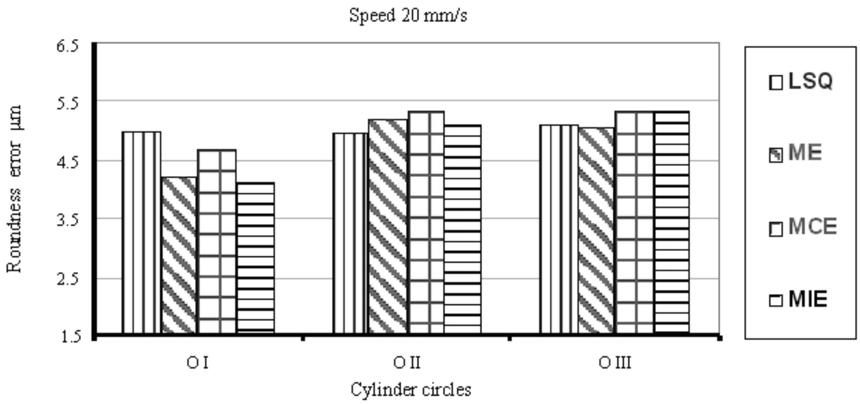

Fig. 9. Measuring errors of fitting algorithms at 20 mm/s for three detection circles.

Figure 8 appears the density of measured points for roundness error using different four fitting algorithms of three transverse circles at probe scanning speed of 20 mm/s. Roundness errors as functions of the fitting techniques are shown in Fig. 9. Analysis of the results indicates that:

- Measurements of *circle I* have a maximum error of 4.10 µm for MIE fittings and a maximum error of 4.98 µm for LSQ response of an error range of 0.88 µm.
- Roundness error ranges of both *circle II and III* have 0.40 µm (5.35 and 4.95 µm) and 0.28 µm (5.35 and 5.07 µm).
- Error difference related to the fitting technique for three measured circles has a maximum value of 1.25 µm (5.35 and 4.1 µm) for MIE fitting response and a minimum value for the same measurements 0.15 µm (5.10 and 4.95 µm) for LSQ and 0.97 µm for ME fittings.

4.5. Probe scanning speed 25 mm/s

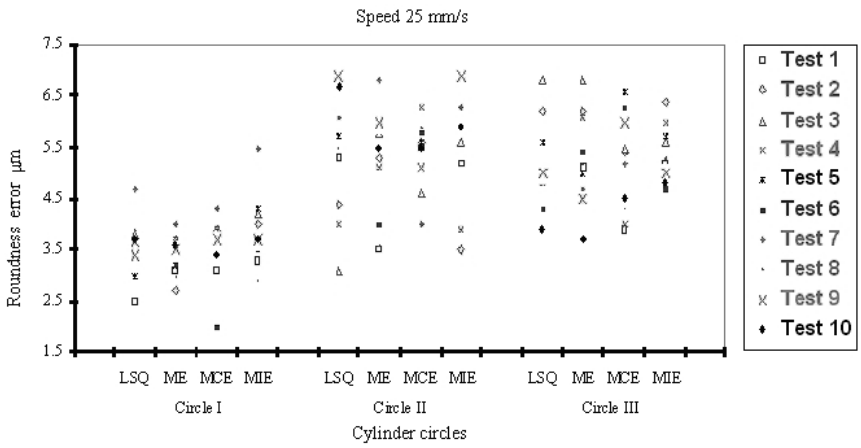

Fig. 10. Measuring errors variation of fitting algorithms for three circles at scanning speed of 5 mm/s.

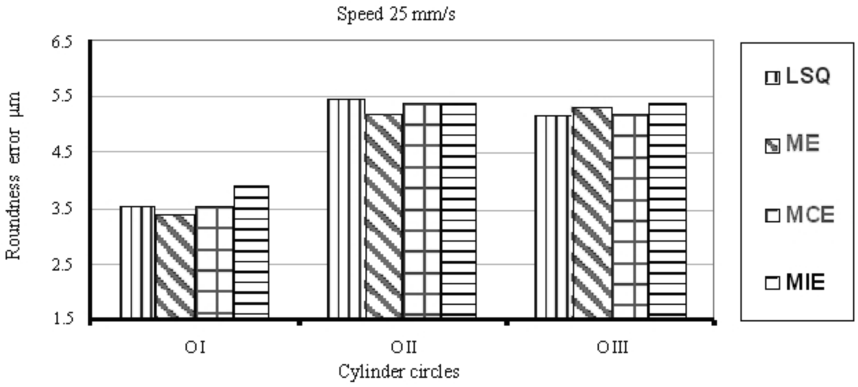

Fig. 11. Roundness errors of fitting algorithms at 25 mm/s for three detection circles.

The presentation of results in Fig. 10 shows density of measured points for roundness error using different four fitting algorithms of three transverse circles at probe scanning speed of 25 mm/s. Roundness errors as functions of the fitting techniques are shown in Fig. 11. Analysis of the results indicates that:

- Measurements of *circle I* have a minimum error of 3.37 µm for ME fittings and a maximum error of 3.89 µm for ITE response of an error range of 0.52 µm.
- Roundness error ranges of both *circle II and III* have 0.27 µm (5.44 and 5.17 µm) and 0.21 µm (5.38 and 5.17 µm).
- Error difference related to the fitting technique for all three measured circles has a maximum value of 1.9 µm (3.54 and 5.44 µm) and (3.37 and 5.27) for both LSQ and ME fitting methods and a minimum value for the same measurements 1.49 µm (5.4 and 3.89 µm) for MIE and 1.88 µm for MCE fittings.

4.6. Probe scanning 30 mm/s

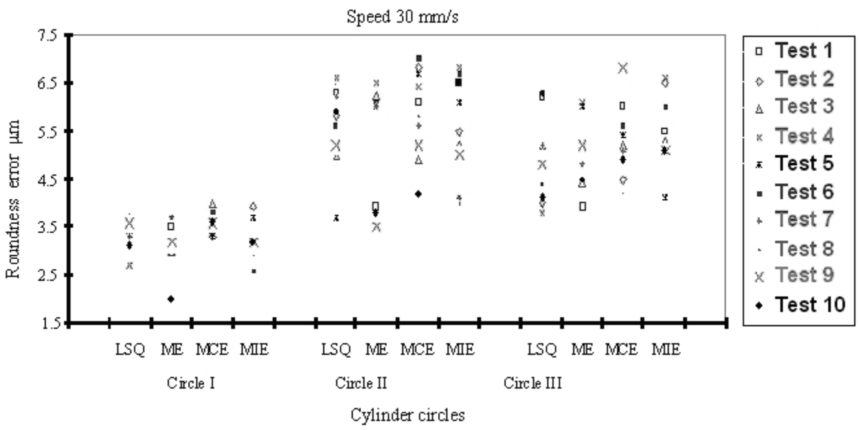

Fig. 12. Roundness errors variation of fitting algorithms for three detection circles at 5 mm/s.

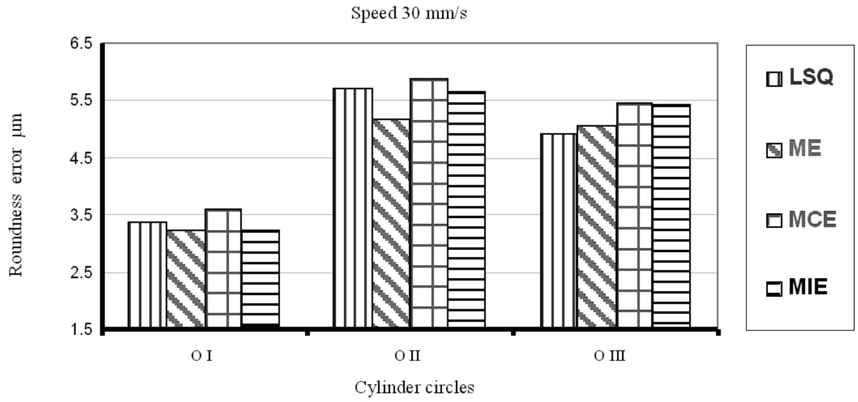

Fig. 13. Measuring errors of fitting algorithms at 30 mm/s for three detection circles.

Figure 12 appears the density of measured tests for roundness error using different four fitting algorithms of three different circles at probe scanning speed of 30 mm/s. Measured error results of roundness for fitting probe 30 mm/s are given in Fig. 13 for the detection circles. From the signal analysis it can be noticed that:

- *Circle I* measurements have the lowest roundness error 3.21 µm for the ME fitting method, and the highest error of 3.56 µm for the MCE fitting method. Consequently, *circle I* has a measuring error range of 0.35 µm.
- Detection *circle II* measurements have a roundness error range of 0.70 µm from 5.87 of MCE fitting method to 5.17 µm of ME fitting method, while measurements of *circle III* have roundness error limits of 5.44 of MCE fitting method and 4.91 µm of LSQ fitting method within an error range of 0.53 µm.

4.7. Probe scanning 35 mm/s

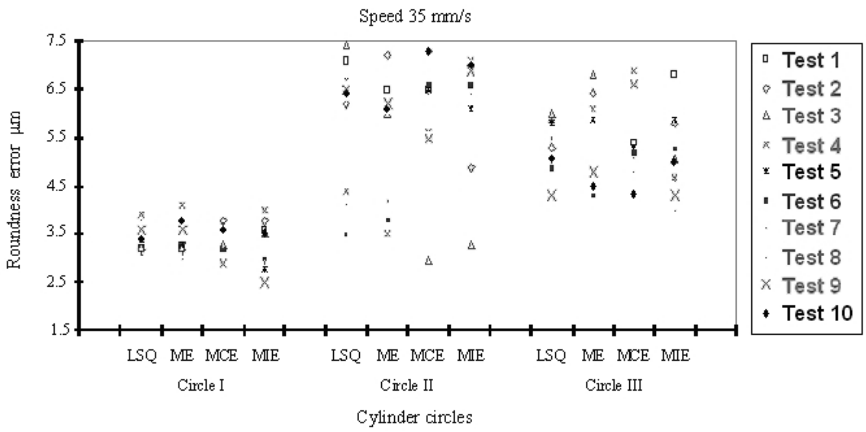

Fig. 14. Measuring errors in the circles using different fitting algorithms.

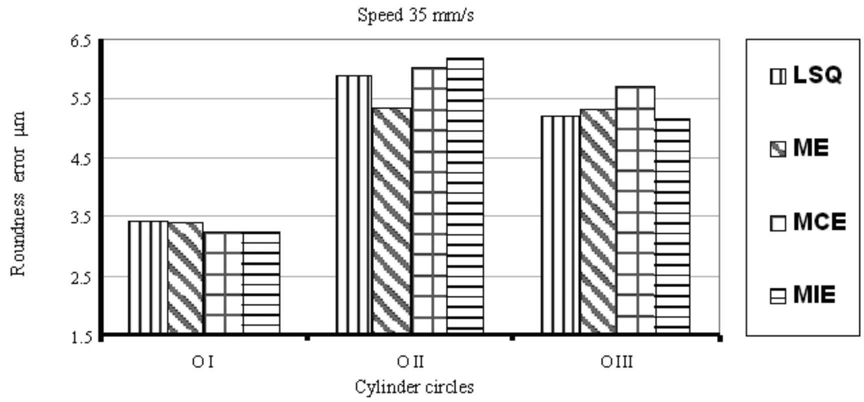

Fig. 15. Roundness errors of fitting algorithms at 35 mm/s for three detection circles.

Figure 14 appears the density of 120 measured points for roundness error using different four fitting algorithms of three transverse circles at probe scanning speed of 35 mm/s. Measured error results of roundness for fitting probe 35 mm/s are given in Fig. 15 for the detection circles. From the signal analysis it can be noticed that:

- *Circle I* measurements have the lowest roundness error 3.25 µm for MCE and MIE fitting methods, the high error of 3.41 µm for the ME fitting method, and height error of 3.43 µm for the LSQ fitting method. Consequently, *circle I* has a measuring error range of 0.18 µm.
- The values of roundness measurement errors for all *circles II* and *III* have high difference of 0.75 and 0.53 µm respectively.

4.8. Probe scanning speed 40 mm/s

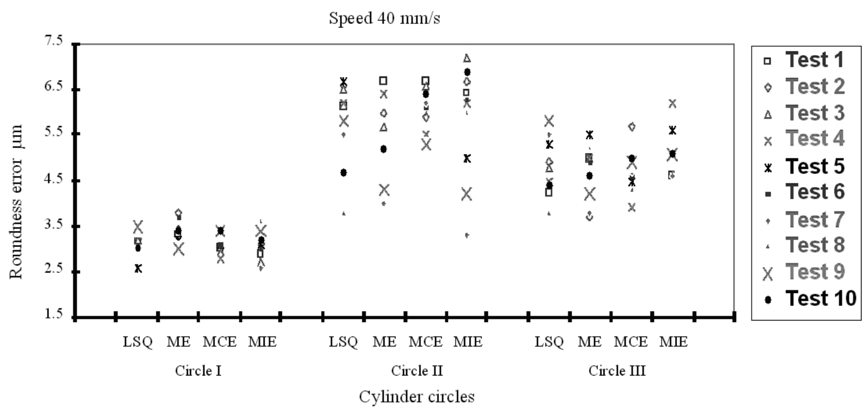

Fig. 16. Roundness errors of fitting algorithms in the three circles using at 40 mm/s.

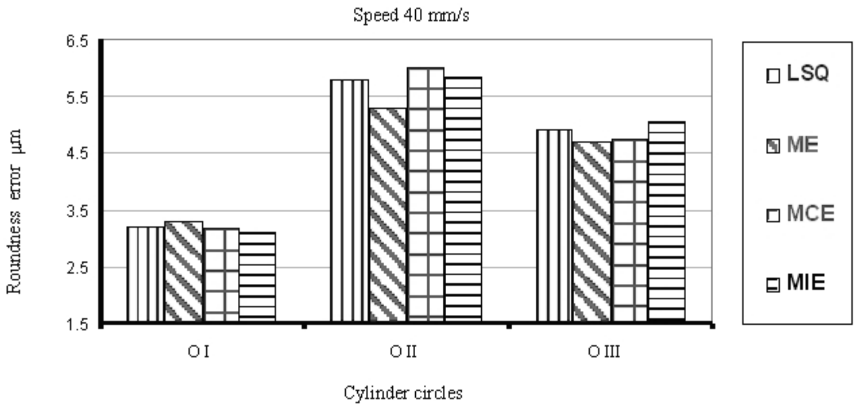

Fig. 17. Measuring errors in the circles using different fitting algorithms.

Figure 16 appears the density of measured points for roundness error using four fitting algorithms of three different transverse circles at probe scanning speed of 40 mm/s. Presentation of given results in Fig. 17 show the measurement errors of roundness detection using different four fitting techniques. Analyses of results illustrate that:

- Roundness measurements of *circle I* have a minimum error of 3.1 µm for MIE fitting and a maximum error of 3.28 µm for ME response, while LSQ fitting error of 3.2 mm and MCE fitting error of 3.16 µm.
- Error measurements of *circle II* have a minimum of 5.28 µm for ME fitting and a maximum error of 5.99 µm for MCE response, while LSQ fitting error of 5.75 mm and MIE fitting error of 5.82 µm.
- Measurement for *circle III* have a minimum error of 4.69 µm for ME fitting and a maximum error of 5.06 µm for MIE response, while LSQ fitting error of 4.9 mm and MCE fitting error of 4.73 µm.
- Error difference for all three measured circles has a minimum value of 0.18 µm (3.28 and 3.1 µm) of *circle I* and a maximum value for the same measurements of 0.71 µm (5.99 and 5.28 µm) of *circle II*.

4.9. Probe scanning speed 45 mm/s

Figure 18 appears the density of measured results for roundness error using different four fitting algorithms of three transverse circles at scanning speed of 45 mm/s. Results given in Fig. 19 show the measurement errors of roundness detection at probe scanning speed of 45 mm/s. Analyses of results illustrate that:

- Measurement of *circle I* have a minimum error of 3.25 µm for MIE fitting and a maximum error of 3.40 µm for ME response, while LSQ fitting error of 3.27 mm and MCE fitting error of 3.35 µm.

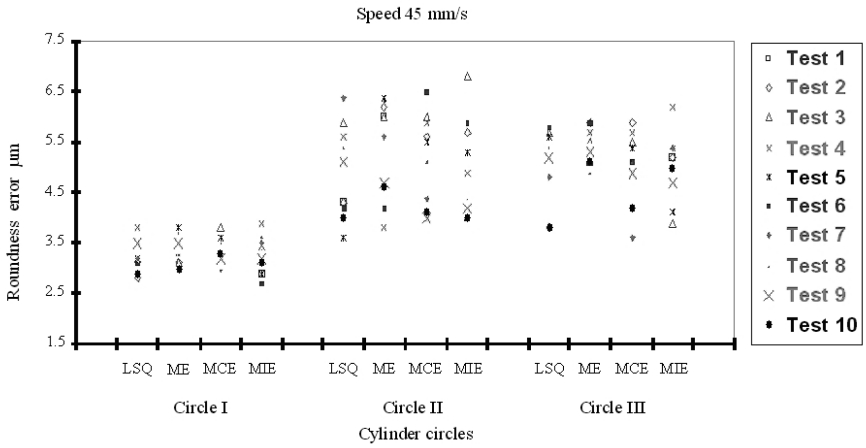

Fig. 18. Roundness errors of fitting algorithms in the three circles using at 45 mm/s.

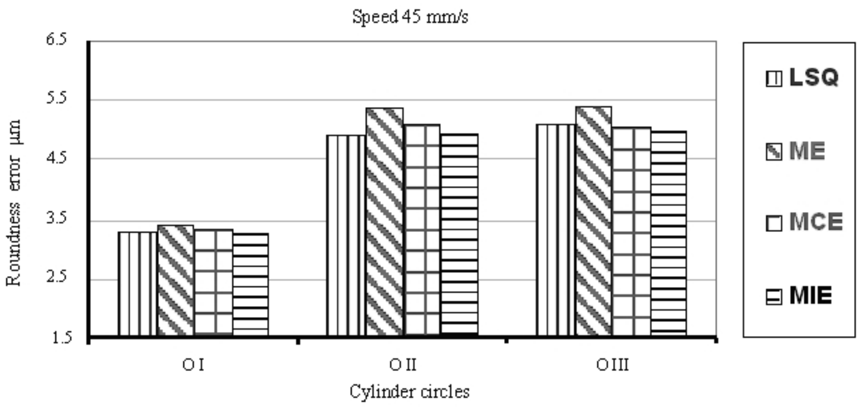

Fig. 19. Measuring errors in the circles using different fitting algorithms.

- Error measurements of *circle II* have a minimum of 4.88 µm for LSQ fitting and a maximum error of 5.38 µm for ME response, while MCE fitting error of 5.11 mm and MIE fitting error of 4.93 µm.
- Roundness Measurement for *circle III* have a minimum error of 5.01 µm for MIE fitting and a maximum error of 5.40 µm for ME response, while LSQ fitting error of 5.09 mm and MCE fitting error of 5.03 µm.

5. STATISTICAL ANALYSIS

To make more reliable analysis of influence of fitting algorithm and probe scanning speed on the CMM measurement accuracy should be using statistical tests. Statistical analysis of roundness error average and standard deviation mean value was calculated for selected parameters. The statistical results obtained are reduced and presented in a more practical and explicit error form in Figs. 20-21. The roundness errors result as function of the nine probe scanning speed using four fitting techniques given as follows:

5.1. Standard deviation average of roundness measurement error

Table 2. Standard deviation variation related to the probe speeds at different fitting algorithms.

Probe speed, mm/s	Standard deviation mean values, μm					
	LSQ	**ME**	**MCE**	**MIE**		SD_{Mean}
5	0.3000	0.4700	0.8500	1.0600		0.6700
10	0.3000	0.3583	0.8167	1.0000		0.6188
15	0.3200	1.3334	1.1434	2.2533		1.2625
20	0.3500	1.3333	1.4800	2.0300		1.2983
25	0.4000	1.1867	1.3634	2.1567		1.2767
30	0.4000	1.1934	1.3967	2.0567		1.2617
35	0.4000	1.2634	1.3734	2.1834		1.3051
40	0.4000	1.1967	1.3367	2.0300		1.2409
45	0.4000	1.2800	1.4000	1.8534		1.2334
						$SD_{Average}$
SD_{Mean}	0.3633	1.0684	1.2400	1.8471		1.1297

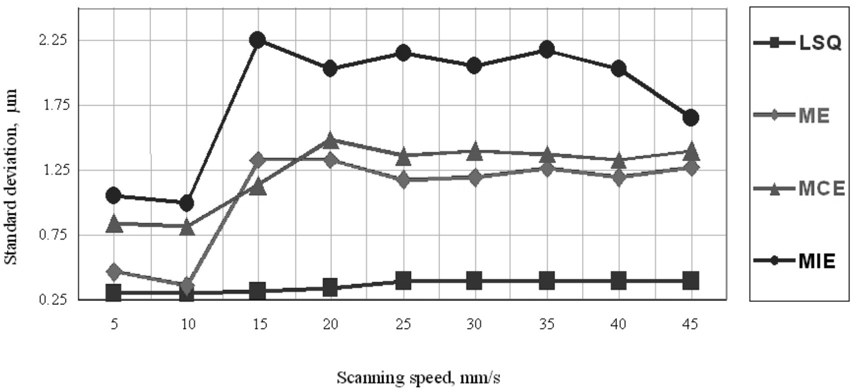

Fig. 20. Standard deviations mean values of fitting algorithms at different probe speeds.

Averaging of standard deviation error of the three circle signals are related to the fitting algorithm for the probe scanning speeds given in Table 2 and presented in Fig. 20. The results indicate that:

- Signal measured for evaluated test samples has a global average of 1.13 μm. The samples at probe scanning speeds from 5 to 45 mm/s (with 5 mm/s interval value) have the averaged values 0.62 to 1.31 μm, which correspond to represent 59.3, 54.8, 111.8, 115, 113, 111.7, 115.5, 109.8 and 109.2 % of the global average respectively. It ensures that measurement at probe speed before 15 mm/s is the suitable case for this work piece to satisfy the high level of accuracy.

- The roundness standard deviation has significant variation at 15 mm/s for all fitting methods; this may be due to probe response at resonance travelling speed.
- The MIE algorithm has highest standard deviation average response, while the LSQ algorithm has accurate response within the application range.

5.2. Roundness error of scanning speed response

Table 3. Roundness errors mean values related to the evaluation fitting algorithm at different probe speeds.

Probe speed, mm/s	Roundness error mean values, μm				
	LSQ	**ME**	**MCE**	**MIE**	RON_{Mean}
5	2.2867	2.0533	2.2800	2.2200	2.2100
10	1.9333	1.7000	1.8133	2.0200	1.8667
15	4.8933	4.7867	4.8433	4.7800	4.8258
20	5.0100	4.8267	5.1233	4.8500	4.9525
25	4.7100	4.6033	4.6900	4.8900	4.7233
30	4.6500	4.4767	4.9567	4.7633	4.7117
35	4.8433	4.6867	4.9800	4.8667	4.8442
40	4.6367	4.4167	4.6267	4.6600	4.5850
45	4.4133	4.7267	4.4967	4.3933	4.5075
					$RON_{Average}$
RON_{Mean}	4.1530	4.0308	4.2011	4.1604	4.1363

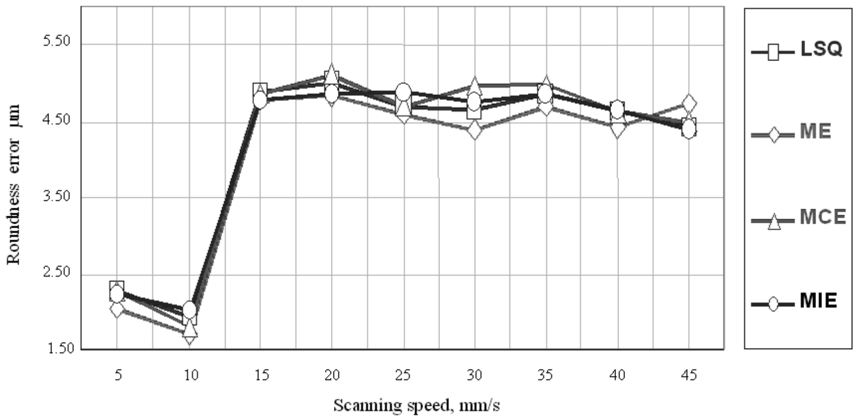

Fig. 21. Influence of probe scanning speed on the roundness error for different fitting techniques.

Averaging of roundness measured error of 50 mm ring circle signals of the fitting algorithms for probe scanning speed are given in Table 3 and presented in Fig. 21. The illustrated values indicate that:

- Signal measured for 1080 evaluated samples has a global average of 4.14 μm. The samples at probe scanning speeds of 5, 10, 15, 20, 25, 30, 35, 40 and 45 mm/s have the averaged values 2.21, 1.87, 4.83, 4.95, 4.72, 4.72, 4.84, 4.59 and 4.51 μm, which correspond to represent 53.4, 45.1, 116.7, 119.7, 114.2, 113.9, 117.1, 110.9 and 108.97 % of the global average respectively. It ensures that measurement at probe speed 10 and 5 mm/s are the suitable case for this work piece to satisfy the high level of accuracy.
- Averaged percentage errors as a function of the fitting algorithm response with respect to the global mean value are 100.4, 97.5, 101.6, and 100.6%, which are corresponding to LSQ, ME, MCE, and MIE respectively. Quality of measurements indicates that MCE and MIE methods have about 1.6% and 0.6% inaccuracy, while the LSQ algorithm has accurate responses with the error range of 0.4%.
- The roundness measurement error range has sharp significant variation at 15 mm/s compared to 5 and 10 mm/s scanning speeds.
- From the data presented in Fig. 21, the values have been treated statistically using polynomial regression type to get general formulae of the roundness error (*RON*) in μm as a function of probe scanning speed *S* for the different four fitting algorithms as follows:

$$RON_{(LSQ)} = 0.006S^4 - 0.1079S^3 + 0.5057S^2 + 0.1484S + 1.4213, \tag{1}$$

$$RON_{(ME)} = 0.0081S^4 - 0.1429S^3 + 0.6887S^2 - 0.175S + 1.3615, \tag{2}$$

$$RON_{(MCE)} = 0.0078S^4 - 0.1464S^3 + 0.7823S^2 - 0.556S + 1.8827, \tag{3}$$

$$RON_{(MIE)} = 0.006S^4 - 0.1111S^3 + 0.5452S^2 + 0.0196S + 1.4927. \tag{4}$$

From the above empirical Eqs. (1-4), the formulae illustrate that the MCE and MIE methods have higher error potentials of 1.9 and 1.5 μm to the probe scanning speed respectively, where ME technique has a lowest error potential of 1.36 μm at high sensitivity coefficients of 0.18 to the probe scanning speed (*S*). The LSQ method has an error potential of 1.4 μm at sensitivity coefficients of 0.15 to the probe scanning speed and sensitivity coefficients of 0.5 μm to the probe scanning acceleration.

6. CONCLUSIONS

This paper presents a new experimental investigation to improve the roundness measurement accuracy of a **C**oordinate **M**easuring **M**achine (**CMM**) for particular measurement tasks. The method proposed requires just two selections of probe scanning speed and fitting algorithm for measuring the roundness of circles.

From this study to improve roundness measurement quality, some conclusions can be drawn:

- There are roundness differences in the same work piece detecting circles; this may be due to selection of different fitting algorithms which have difference responses according to their software design within the maximum permissible scanning probing error.
- Suitable scanning speed of the machine touch probe should be well selected in accordance with the fitting algorithm to get high response quality with accurate roundness measurement.
- For similar roundness measurements, ME algorithm show high quality response beside high sensitivity coefficients to the probe scanning speed; both treatment methods ensure high measuring accuracy at low probe scan speed may be due to probe design resonance.
- Mean average of roundness error may be the reliable tool for CMM accuracy evaluation compared to standard deviation average within the application range.
- The range of roundness measuring error has the high significant value at 15 mm/s compared to 5 and 10 mm/s testing speeds for all fitting techniques. Result in the selected speed obtained significant variations, may be due to probe response at resonance travelling speed.
- Finally, the most basic measuring applications, the measurement of supplemental standard ring will increase our knowledge about the state of the measuring strategy.

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