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METHOD OF OPTIMAL MEASUREMENT STRATEGY FOR ULTRA-HIGH-PRECISION MACHINE IN ROUNDNESS NANOMETROLOGY

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Abstract-Talyrond-TR is a modern sensitive instrument in nanometrology. The performance of Talyrond-TR machine is very important to find an optimal result in roundness measurement. In this paper, the experimental evaluation method of Talyrond-TR 73 machine is designed by using reference standard hemisphere. The influence of Talyrond machine performance in roundness measurement is presented. Signal responses of ten metrological strategic parameters have been analyzed and discussed. Deviation in roundness measurement strategies corresponding to four reference algorithms (LS), MZ, MC; MI) and two software fitting filters (2CR and Gaussian) with four spectral frequency ranges (1:15, 1:50, 1:150; 1:500 upr) are obtained through repeated arrangement, comparison and achieved. Experimental results revealed that the lowest deviation in roundness has been investigated by using MZ reference algorithm. The average of total roundness indicates low deviation by about 65.6% and 57.3% at using 2CR- and Gaussian-filter respectively, which proved the machine reliability within application range. Furthermore, the evaluation method was performed experimentally to establish reference data sets for circular, cylindrical and spherical objects. The sets of established data at different strategic parameters have been postulated to satisfy the ability of the proposed method to correlate the roundness measurements within the application range. The experimental result ensures that the proposed evaluation method is reliable and effective. Moreover, expanded uncertainty in measurement has been estimated and confirmed the degree of confidence for the proposed method.

Index terms: Nanometrology, Talyrond instrument, roundness, reference algorithms, software fitting filters, uncertainty and evaluation method.

I. INTRODUCTION

Geometrical form in the dimensional metrology is the very important feature of quality control for mechanical products. Roundness is an essential geometrical feature especially for rotating parts in aerospace, nuclear reactors and automotive applications, which need accuracy and precision within minimum deviation in the measurement. In manufacturing metrology, the roundness feature can be checked using modern sensitive systems. In addition, many dynamic operations require examining roundness form of rotating parts to ensure their validity to work by roundness instruments which describe the condition on a rotating surface, where all points of the surface must intersect. The production quality of rotating parts is typically influenced by many different parameters related to workpiece finishing, environmental interaction, measuring machine performance and operator experience. The importance of the study for roundness deviation in measurement of circle feature is a vital part to avoid the excessive lateral or axial runout deviation of rotating and reciprocating parts during machining process, dynamic operation and calibration method. The calibration of standard reference artifact that is used in the accuracy verification of roundness instrument is also very an important requirement. Therefore, the validation accuracy of software strategies for measuring machine becomes very important [1-2].

Standard measuring methods for roundness measurement are commonly using in coordinate measuring machine, continuous (scanning) and discontinuous (discrete) method. Continuous method is individual mode, because positions of data results are consecutive at measuring surface. Therefore, the idea of roundness measurement using Talyrond machine as a touch-sensitive instrument builds on the way continuous (scanning) method. Generally, there are many sources of error in measurement methods. Researchers found: it is difficult to separate the error resulting from the stylus vibration and the measured surface in roundness measurement [3-7]. High attention is dedicated for evaluation methods to be suitable use for roundness measuring instruments.

The quantum metrology is the physical study of high-resolution systems and highly sensitive measurements depends on quantum theory to describe the physical systems, particularly exploiting quantum entanglement [8], where the measurement of deviation error is classified as an approach of quantum metrology. Thus, the current work is conducted to evaluate the quantum dynamic behaviours of Talyrond machine as metrological strategies using simple experimental method. This method of evaluation is designed corresponding to ten measurement strategic parameters. The roundness software version: 5-0.1 for Talyrond-TR 73 machine equipped with HPR mode is studied and discussed in detail. These ten parameters included four types of circle reference algorithms, two types of computerized software fitting filters, and four ranges of spectral wave numbers using undulations per revolution (upr) as band pass key factors. The program of this work is appropriate and available as an activity provided for the National Institute for Standards (NIS), Egypt. The main objective is to eliminate the repeatable deviation in trial operation during measurement, verification or calibration processes. The goal is to reduce costs according to consuming measurement time and evaluate figure accuracy of visible roundness measurement. So, this research work aims to develop the roundness measurement methodology as an error compensation method for the purpose of get the best deviation at the optimal measurement strategy. This study is also very important for the software designer to develop new version of precision machines. Moreover, the prediction of effectiveness evaluation method will be very useful and precise.

II. BACKGROUNDS AND MOTIVATIONS

The history of roundness measurement systems is reviewed in this section, and then the stages of software filters that use in the Talyrond machine are also reviewed. In order to gives a scientific background for readers. Historically, roundness measurement was based on use of simple tools such as dial indicator. While from the achievement of the industrial revolution, roundness instruments were setup based on one of two types of machines. The first one is called Talyrond machine was manufactured by RTH (Rank Taylor Hobson Ltd). While the second way is coordinate measuring machine (CMM). Roundness measurement using Talyrond machine is based on one of two versions of configuration. Configurations of Talyrond machine have either rotating table or rotating spindle (hydrostatic). The most common type is the hydrostatic spindle configuration version. The rotating pick-up version of the instrument was first made; this was termed ‘RTH Talyrond-1’ was developed later. The instrument like RTH Talyrond-TR 73 HPR (high precision roundness) machine becomes one of important tools in national metrology institutes (NMIs) [9-10]. The standard RTH Talyrond-TR 73 machine has three accurate orthogonal axes and equipped with high sensitive touch probe. Therefore, it is much distinguished of Talyrond-TR 73 machine that the force of touch probe tip to the object surface is very small up to less than one Newton. The Talyrond-TR 73 probe cantilever is brought into contact with the inner or outer circular surface of object being measured at a recorded position. In the measurement process, the probe of stylus profiler senses the surface height through mechanical contact directly, while the stylus traverses the peaks and valleys of the circular surface of the object with very small contacting force. The horizontal motion of the stylus tip is converted to an electronic signal by a transducer. A number of points are taken around the component and these are then combined in computer software to determine the roundness form of the object, which represents the curricular surface profile. It can be say, roundness profile is a series of harmonic sine waves which are added together to produce the complete surface profile.

The study of the Talyrond-TR 73 machine software is very important from the metrological point of view to find an optimum strategy in roundness measurement. Therefore, the data analysis of the Talyrond-TR 73 software can contribute significantly to the roundness measurement accurately. It can be said that some influencing parameters of measuring machine software strategy and metrologist experience have effective reactions on the quality of measurement.

Beside the aforementioned approach, the standardization of filtration techniques is also important issue. The ISO/TS 16610 presents a category of modern advanced filtration techniques technology in surface metrology. These filters include Gaussian filter, spline filter, robust filter, morphological fitter, wavelet filter, cascading filter and other segmentation filters [11-12]. It provides a powerful and useful software toolbox of filtration techniques, allowing metrologist to analyze various surface characteristics. Most of fitting filters could date back to two basic traditional filtration techniques emerged since 1950s, i.e., the Mean-line based system (M-system) and the Envelope based system (E-system) [11]. The M-system generates a reference line passing through the measured profile from which the surface waviness was assessed. The reference line was called the mean line due to the fact that the profile portions above and below the reference line are equal in the sum of their areas, see figure 1. The first practical mean-line filter used in surface characteristic measurement is the analogue filter proposed by Reason in 1961 [13], which was constructed by two-capacitors -resistors (2CR) network. However, this 2RC filter was suffered by the phase error and profile deformation due to filtering. Whitehouse and Reason [14] simulated a research work in 1963, the 2RC filter digitally. This work described the filter using a weighting function that depended on the cutoff wavelength. While, Whitehouse in 1967 [15], made digital filters and introduced phase-corrected filter also. While, the phase-corrected digital filter was still has some problems, such as it badly distorted the profile at the end. After those, the Gaussian digital (mathematical) filter was chosen as the new filter for separating differing wavelengths [16]. The Gaussian filter is a typical mean-line based filter whose process is a convolution operation of the surface under evaluation and the Gaussian weighting function [11]. In 1965, the E-system was initially developed by Weingraber [17]. The E-system is acting totally differently than the M-System. It appeared as a large disk rolling across over the profile from above, and the covering envelope formed by the rolling disk followed by the compensation of disk radius. The envelope was viewed as the reference profile. The E-system gains its basis from the simulation of the contact phenomenon of two mating surfaces, whereby peak features of the surface play a principal role in the interaction operation, see Fig.2.

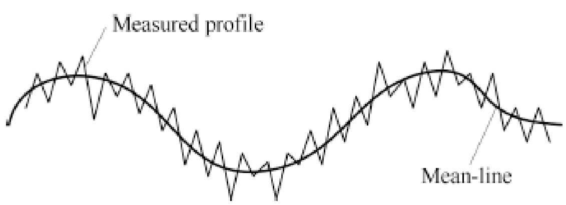


Figure 1. The mean-line system (M-system)

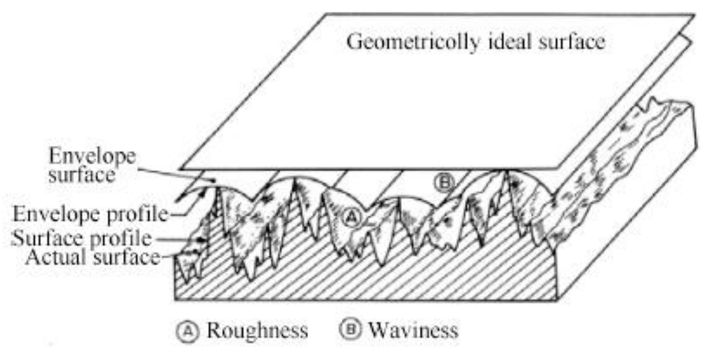


Figure 2. The envelope system (E-system)

Between 1955 and 1966 [18], some arguments between the M-system and the E-system in terms of their capability and superiority have been made. When that time, the difficulty appeared in building practical instruments for the E-system as two elements were needed: a spherical skid to approximate the enveloping circle" and a needle-shaped stylus moving in a diametral hole of the skid to measure the surface waviness or roughness as deviation with respect to the generated envelope. The standing objection from Reason [14] was that the choice of the rolling circle radius is as arbitrary as the choice of cutoff in the M-system, and no practical instrument using mechanical filters could be made. However, the facts proved that the M-system and the E-system are complement to each other, rather than compete against each other and none of them can fulfill all the practical demands by themselves alone [11, 19].

Motivated by modern product design plans, modern products and measurement machines are equipped with sophisticated surfaces to achieve desired functions. In response to these technology advancements, filtration techniques are motivated to be enhanced in their capability and performance with dealing with functional surfaces. Thus, the M-system was greatly enriched by incorporating advanced mathematical theories. The Gaussian regression filter overcame the problem of end distortion and poor performance of the Gaussian filter in the presence of significant form component [11, 20], while the robust Gaussian regression filter solved the problem of outlier distortion in addition [21-22]. The spline filter is a pure digital filter, more suitable for form measurement [23]. The robust spline filter is insensitive with respect to outliers due to their closed loping [24-25]. Nowadays, research funding is still going on in full swing to innovate combined filters by software designers in R&D departments [11, 26-29]. The E-system is also experienced significant improvements [26]. By introducing mathematical modeling, morphological filters emerged as the superset of the early envelope filter, but offering more tools and capabilities. The basic variation function of morphological filters includes the closing filter and opening filter. Morphological filters could be combined to achieve superimposed effects, referred as the alternating symmetrical filters leads to scale-space techniques [27]. On the other hand, Gaussian- and 2CR-filters are currently standardized fitting filters [30] and still working in newly instruments such as CMM machine and Talyrond-TR 73 machine because their simplicity, accuracy and flexibility. Therefore this research is planned to conduct optimal measurement strategy in NIS laboratory.

III. EXPERIMENTAL WORK

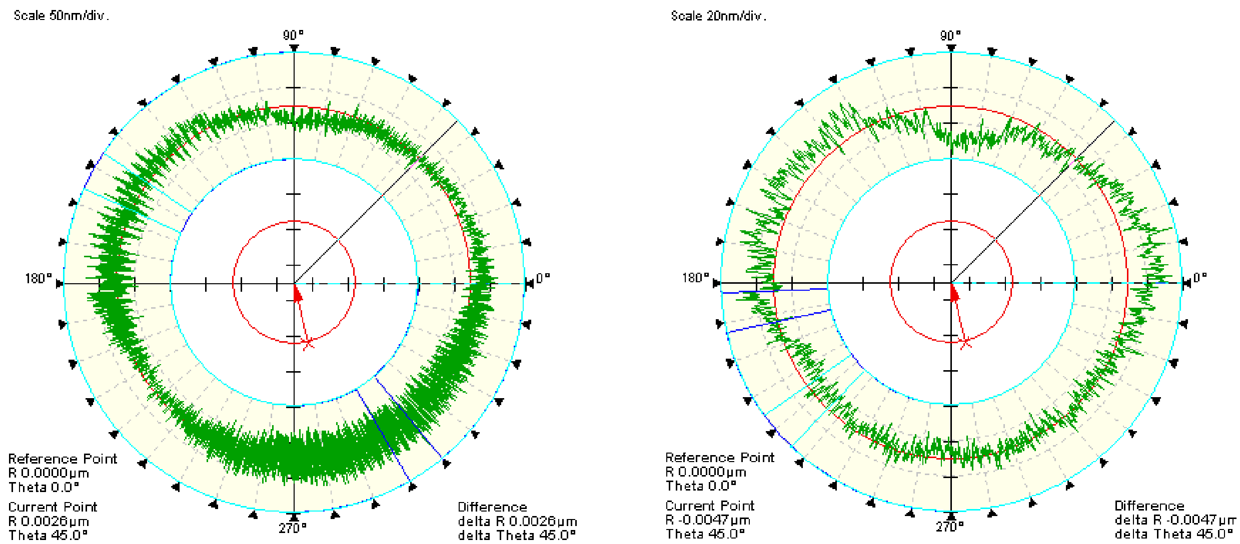
The evaluation method of measurement strategies for roundness machine software through carrying out signals is presented experimentally. The method includes ten software parameters of Talyrond-TR 73 machine. The experiment work consists of five main steps of the instrumentation system: fixing the hemisphere object in the test position center, verification of stylus contact, a data generator, circle reference algorithm, fitting filter, and a comparator to analyze and interpret the monitoring results. The artefact object was cleaned and located in the test position at interposition center on machine table. The measured object is standard accurate spherical surface. The Talyrond machine was turned on to check the electric power switches, hydrostatic-bearing spindle rotation, and stylus speed. Where a Hatchet styles tip of the long type has been selected and calibrated according to the machine manual. Measurement strategies of the Talyrond-TR 73 RTH machine have two types of software fitting filters and four reference algorithms of circlers at four different spectral wave responses. The software filter (Gaussian or 2CR) is used in the evaluation method of roundness deviation. The circle reference algorithms as Least Square (LS), Minimum Zone (MZ), Minimum Circumscribed (MC) and Maximum Inscribed (MI) have been used. The background of circle reference algorithms was described through previous research of the author [31]. The spectral wave numbers of machine software which include dominant harmonics wave range from 1-15, 1-50, 1-150 to 1-500 upr have been used. The measurement strategy and stylus scanning speed were selected and primary tested in recommended environmental conditions. The Talyrond-TR 73 machine has been verified and accepted within standard specification according to ISO/TS 12181-1/2 [32-33]. A metrological inspection of the surface of circular feature is measured and presented.

Relevant influences in the roundness deviation measurement have been taken into account according to standards. The specification of measuring conditions, used stylus including Talyrond-TR 73 test machine are presented in Table 1.

Table 1: Specification of RTH Talyrond TR 73 HPR instrument and used stylus

Software code no.	: M 112/2266-02
Software version	: V5 - 0.1
Measurement direction	: Anti-clockwise
Attitude	: Vertical
Stylus no.	: K42/3827 TR 73 1.27 mm Hatchet
Measurement speed	: 6.0 rpm
Angle range trace	: 360^o

Figure 3 illustrates typical monitoring results of roundness measurement using datum spindle. The preliminary result shows that the roundness measurement in figure 3b is substantially enhanced compared with that shown in figure 3a, due to the effect of software filter parameter.



(a) Roundness without any filter (unfiltered) (b) Roundness using Gaussian-filter

Figure 3. Typical output results of roundness using TR 73 instrument

The result analysis of software parameters and their validation is another major challenge in this work. Experimental procedures of roundness measurement are repeated 10 times for testing software filters, circle reference algorithms and spectral wave numbers have been studied of each strategy in measurement. In this research**,** 100 test results of software parameters have been investigated in order to reach the optimum evaluation for roundness deviation. This is to predict the effect of spectral wave numbers on measurements at ten different software parameters as follows:

a. Roundness deviation at two different software fitting filters.

b. Roundness deviation at four different reference circle algorithms with Gaussian-filter.

c. Roundness deviation at four different reference circle algorithms with 2CR-filter.

IV. RESULTS AND DISCUSSION

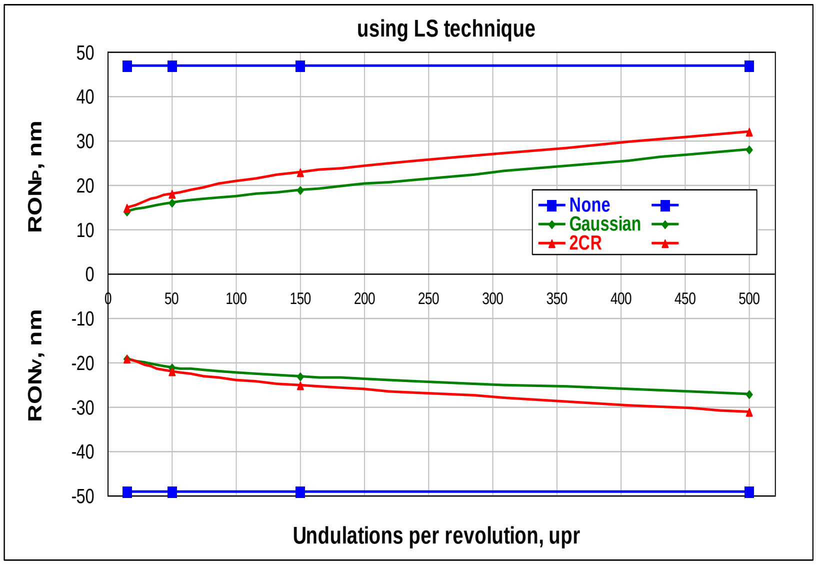
a. The effect of software fitting filters on roundness deviation

Peak and valley signals (RON_P; RON_V) can represent half power radius for roundness feature measurement using Talyrond-TR 73 machine. The total roundness (RON_t) is the distance between highest peak-to-valley response signals of the form profile. Effects of different software fitting filters on the roundness feature have been measured. Thus, the separation process of signals using LS reference algorithm in rest of the roundness measurements has been installed. Effects of two types of software filters on the peak and valley response signals have been tabulated in Table 2 to compare the deviation in measurement. Figure 4a shows the effect of Gaussian-, 2CR-filter and unfiltered on the peak and valley response signals using LS algorithm at different spectral wave numbers. It illustrates that, whenever increased spectral wave numbers in roundness measurement, the deviation than increases for each filter. While, when there is not any filter used (unfiltered), the RON_t response would not exceed 49 nm despite a change of spectral wave numbers. Therefore, the result has confirmed that the use of the Gaussian-filter gives minimum deviation response using LS reference algorithm within application range.

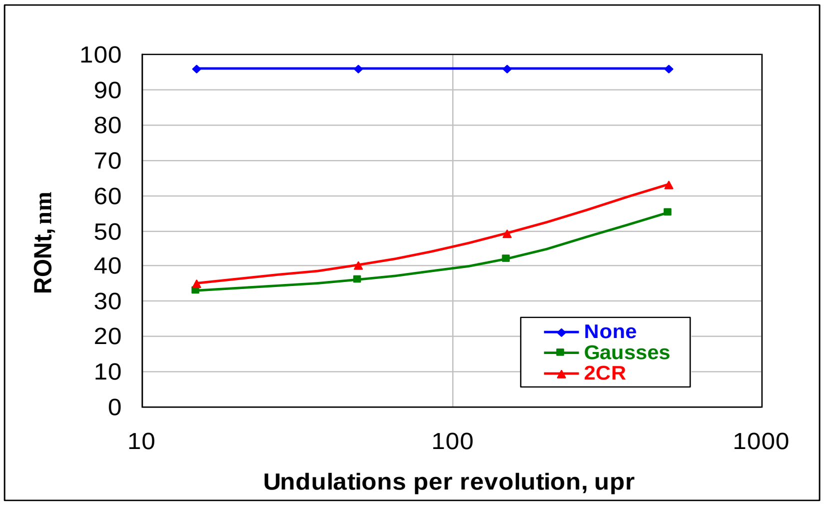
Table 2: Roundness deviation at different parameters using LS algorithm

Frequency	Peak roundness deviation, RON_P (nm)			Valley roundness deviation, RON_v (nm)		
	None	Gaussian	2 CR	None	Gaussian	2 CR
1-500	47	28	32	49	27	31
1-150		19	23		23	25
1-50		16	18		21	22
1-15		14	15		19	19

Figure 4b shows the effect of software fitting filters on RON_t output signals using Gaussian-filter, 2CR-filter and unfiltered at spectral wave numbers changes at using the LS algorithm. It is noticeable that with the any increase of the upr, the RON_t will directly increases. While the total value of roundness (RON_t) almost constant at unfiltered (blue) despite the any change in upr. Analysis of results confirmed that, the use of the Gaussian-filter gives lowest deviation of RON_t measurement at the certain conditions. While the impact of software filters and reference circle reference algorithms still needs more accurate analyses to establish reference data set in roundness nanometrology.



(a) Peak and valley roundness deviations ($RON_{P;}$ RON_V)



(b) Total roundness deviation (RON_t)

Figure 4. Influence of spectral wave numbers (upr) on the roundness

b. The Effect of circle reference algorithm with Gaussian-filter on roundness deviation

Mmeasured signal at using Gaussian-filter has lowest geometric deviation error compared to 2CR-filter, figure 4. According to this result under the ISO 12181-1 [32], guides the author to applied the Gaussian-filter in more next measurements in this section. Therefore, the computational effect of Gaussian-filter on the roundness measurement signal at different types of fitting algorithms has been studied. The output result of peak and valley (RON_P; RON_V) signals using Gaussian-filter have been measured and registered in Table 3. Results that appeared within 1 nm, Table 3, they should be zero, may be in the range of uncertainty in measurement. Figure 5 shows the impact of Gaussian-filter response on the peak and valley signals of roundness deviation using four reference algorithms at upr changes. It illustrated that, any increases of spectral wave number leads to increase the deviation in measurement for both peak and valley in each filters. While without use any filter (unfiltered), peak and valley signals of roundness almost zero despites any changes in the upr parameter. It is confirmed that, the use of the MC algorithm with Gaussian-filter gives lower deviation in the peak roundness at certain conditions. While using the MI reference algorithm with Gaussian-filter gives lower deviation in the valley roundness at the same specific conditions.

Table 3: The roundness result (nm) using Gaussian-filter at various algorithms

Frequency	Peak roundness, RON_P (nm)				Valley roundness, RON_v (nm)			
	LS	MZ	MC	MI	LS	MZ	MC	MI
500	28	24	1	51	27	24	66	1
150	19	18	1	38	23	19	51	0
50	16	15	1	36	21	17	45	1
15	14	13	1	27	19	14	40	0

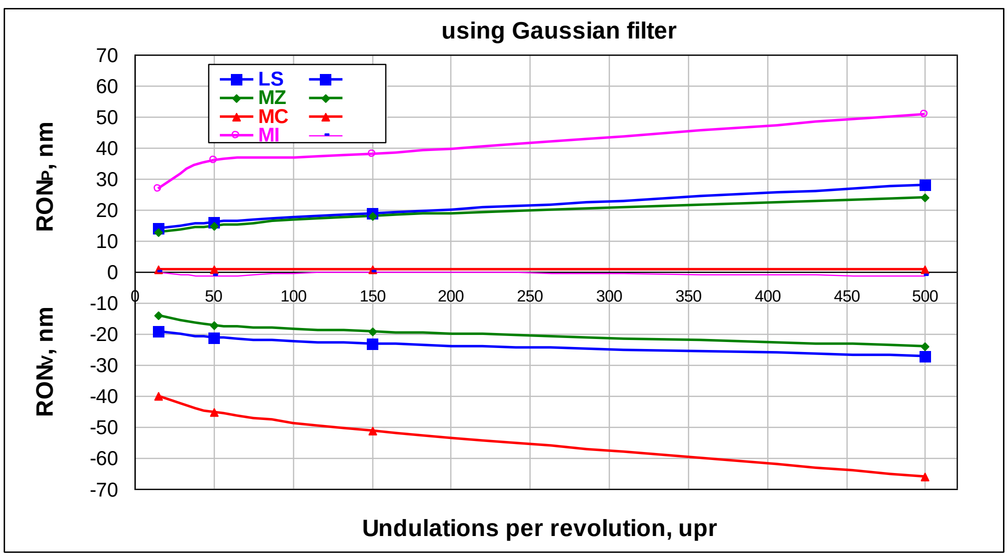


Figure 5. Influence of spectral wave number on the roundness deviation at various algorithms

The computation effects of Gaussian-filter on the RON_t output signals have been registered in Table 4 as seen graphically in figure 6. It shows that the minimum deviation is appeared at using MZ algorithm, while the maximum deviation is appeared at using MC reference algorithm. Therefore, experimental results illustrated that, if the metrologist selects the MZ algorithm with the use of the Gaussian-filter gives lowest deviation in the roundness measurement as seen in the figure 6. These results will be a suitable good guide for the metrologist at using the Talyrond-TR 73 machine.

Table 4: Total roundness results with various algorithms at Gaussian-filter

Frequency	Total roundness, RON_t (nm)			
	LS	MZ	MC	MI
500	55	48	67	52
150	42	37	52	38
50	36	32	46	37
15	33	27	41	27

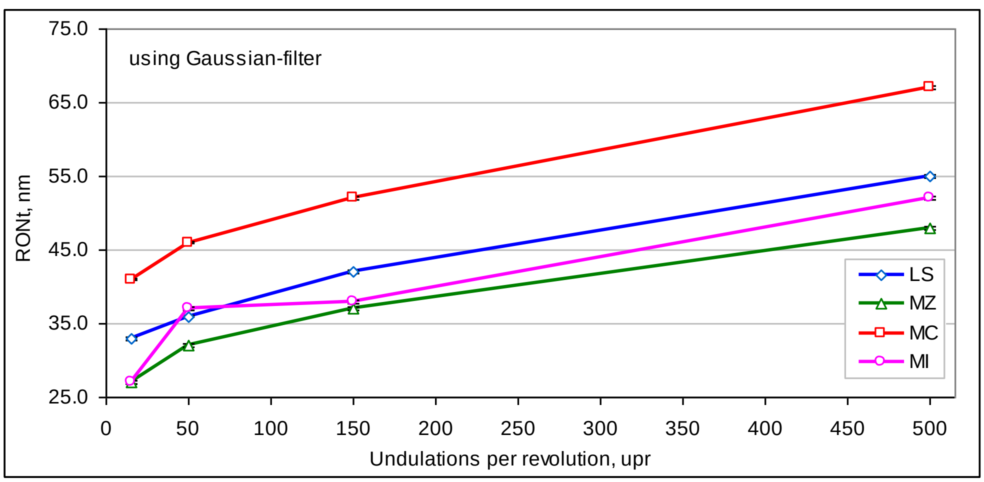


Figure 6. Effects of spectral wave number on the RON_t

From the data presented in figure 6, the analysis have been treated statistically using first order linear regression fit type to get general formulae of the roundness error (RON_t) in nm as a function of undulation per revolution Hz for the different four reference algorithms as follows:

$$\left.\begin{aligned} RON_{LS} &= 0.0436\ upr + 33.713 \\ RON_{MC} &= 0.0501\ upr + 42.536 \\ RON_{MZ} &= 0.0394\ upr + 28.949 \\ RON_{MI} &= 0.0436\ upr + 30.706 \end{aligned}\right\} \quad (1)$$

From linear regression equations (1), the empirical formulae illustrate that the LS and MI algorithms have high error potentials of 33.71 nm and 30.71 nm to the upr, where MC reference algorithm has the highest error potential of 42.54 nm at high sensitivity coefficients of 0.0501 to the spectral wave number (upr). The LS and MI reference algorithms have the same sensitivity coefficient of 0.0436 to the upr. The MZ algorithm has lowest error potential of 28.95 nm at lowest sensitivity coefficients of 0.0394 to the spectral wave number.

c. The Effect of circle reference algorithm with 2CR-filter on roundness deviation

The peak, valley and total deviation signals in roundness using 2CR-filter have been measured and registered in Tables 5 and 6. The result appeared within 1-2 nm, Table 5, they should be zero, may be in the range of uncertainty in measurement. The results show that, when using the MC algorithm with 2CR-filter, the deviation in the peak signal has lowest value and using the MI reference algorithm gives lower error in the valley roundness measurement. But, the lower deviation in the total roundness was clear when using the MZ reference algorithm in certain conditions. Figure 7 shows the influence of 2CR-filter on the peak and valley signals of roundness deviation when using four reference algorithms at different spectral wave numbers. It is concluded that, any increase of upr frequency leads to increases in the roundness deviation for each algorithm. The minimum computational deviation in roundness measurement appears when using MZ algorithm, while the maximum response is observed using MC algorithm in both peak and valley signals. Thus, it can be stated that if the metrologist selects the MZ algorithm in roundness measurement strategy as shows in figure 8. It is guaranteed that the use of the 2CR-filter gives lower deviation at same conditions. The result helps the metrologist to use the suitable reference data set for cylindrical, circular and shear measurements at 2CR-filter on Talyrond-RTH-TR 73 machine.

Table 5: Roundness deviations using four different algorithms using 2CR-filter

Frequency	Peak roundness, RON_P (nm)				Valley roundness, RON_v (nm)			
	LS	MZ	MC	MI	LS	MZ	MC	MI
500	32	30	2	68	31	30	68	0
150	23	21	0	44	25	21	59	0
50	18	17	1	35	22	17	48	2
15	15	15	1	29	19	15	42	0

Table 6: Total roundness values (nm) at different algorithms at 2CR-filter

Frequency	Total roundness, RON_t (nm)			
	LS	MZ	MC	MI
500	63	61	70	68
150	49	42	59	44
50	40	35	49	37
15	35	30	43	29

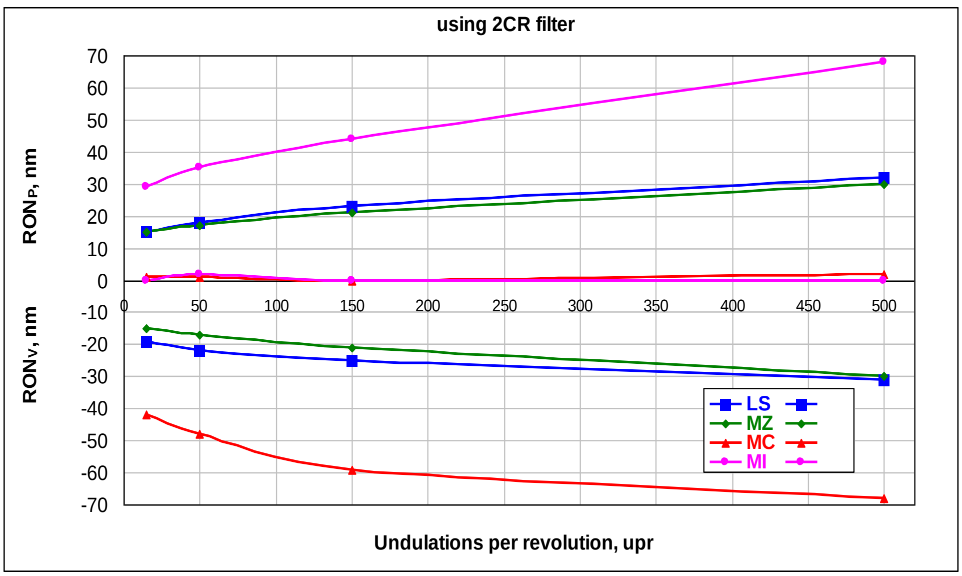


Figure 7. Illustrate the effect spectral wave numbers on the roundness variations

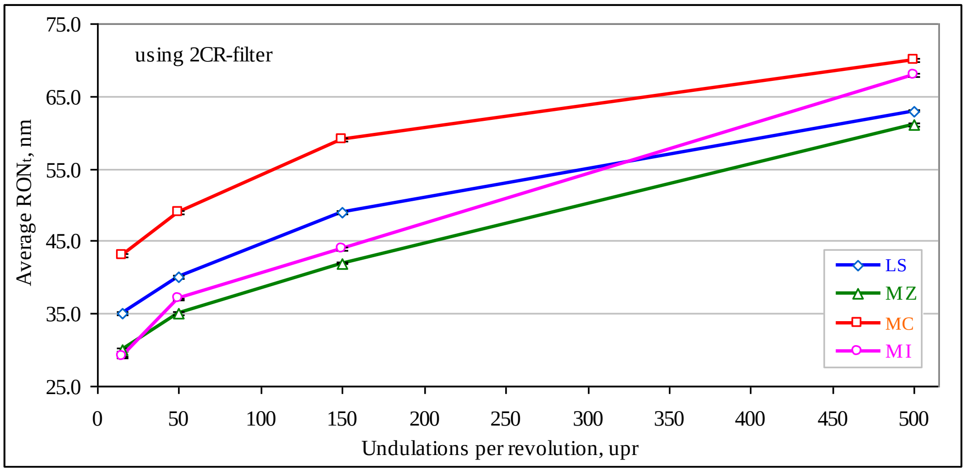


Figure 8. Effects of spectral wave number on RON_t

From the data presented in figure 8, the value analysis have been treated statistically using first order linear regression fit type to get general formulae of the roundness error (RON_t) in nm as a function of undulation per revolution Hz for the different four reference algorithms as follows:

$$\left.\begin{aligned} RON_{LS} &= 0.0539\ upr + 37.112 \\ RON_{MZ} &= 0.0608\ upr + 31.124 \\ RON_{MC} &= 0.0505\ upr + 46.227 \\ RON_{MI} &= 0.0751\ upr + 31.080 \end{aligned}\right\} \quad (2)$$

From linear regression equations (2), the empirical formulae illustrate that the LS and MI reference algorithms have error potentials of 37.11 nm and 31.08 nm to the upr, where MC algorithm technique has the highest error potential of 46.23 nm at the lowest sensitivity coefficients of 0.0505 to spectral wave number (upr). The MZ algorithm has error potentials of 31.12 nm at the sensitivity coefficient of 0.0608 to the upr. The MI reference algorithm has lowest error potential of 31.080 nm at highest sensitivity coefficients of 0.0751 to spectral wave number.

V. RESULT ANALYSIS AND EVALUATION FOR ROUNDNESS DEVIATION

The output values were appeared within 1-2 nm as in Table 3 and Table 5, my resulted due to unexpected vibration or noise during roundness measurement. These values should be zero.

Therefore, we must estimate the uncertainty in the measurement. The computational effects of peak, valley and total deviation for roundness measurement using different parameters have been studied. The relative deviation result in measurement compared to none filter result, presented in Tables 7-9. Table 7 indicates the evaluation of deviation rate of the peak (RON_P) measurement by using Gaussian-, 2CR-filter and unfiltered with LS reference algorism. Table 8 indicates the relative evaluation of valley deviation (RON_v). Table 9 presents the achievement deviation rate of the RON_t at certain conditions. Thus, it can be say that, if the metrologist selects the suitable measurement strategy with Gaussian-filter at LS reference algorithm, the result gives lower deviation of RON_P, RON_V and RON_t especially at 15 upr. The experiment revealed that the highest roundness deviation with 68.1% is achieved at 2CR-filter, while the high average is found by about 59.6% at using Gaussian-filter. Moreover, the average roundness deviation could be highly achieved as 63.3% at using 2CR-filter, while the average of roundness evaluation is found by about 55.1% at using Gaussian-filter. This provides the effectiveness method in roundness evaluation within the application range. On the same direction, figure 9 shows critical coup value of RON_t at 250 Hz when using 2CR-filter, while at using Gaussian-filter appears another coup critical value at 350 Hz. The coup behavior may be due to the computational mathematical design of filters. These coups need further study for carefully interpret.

Table 7: Relative deviation rate of peak roundness result at two different filters using LS algorithm

Frequency	Evaluation in RON_P measurement		
	None	Gaussian, %	2 CR, %
500	47.0	59.6	68.1
150		40.4	48.9
50		34.0	38.3
15		29.8	31.9

Table 8: Relative deviation rate of valley roundness accuracy at two filters using LS algorithm

Frequency	Evaluation in RON_v measurement		
	None	Gaussian, %	2 CR, %
500	49.0	55.1	63.3
150		46.9	51.0
50		42.9	44.9
15		38.8	38.8

Table 9: Relative deviation rate of total roundness accuracy at two filters using LS algorithm

Frequency	Evaluation in RON_t measurement		
	None	Gaussian, %	2 CR, %
500	96.0	57.3	65.6
150		43.8	51.0
50		37.5	41.7
15		34.4	36.5

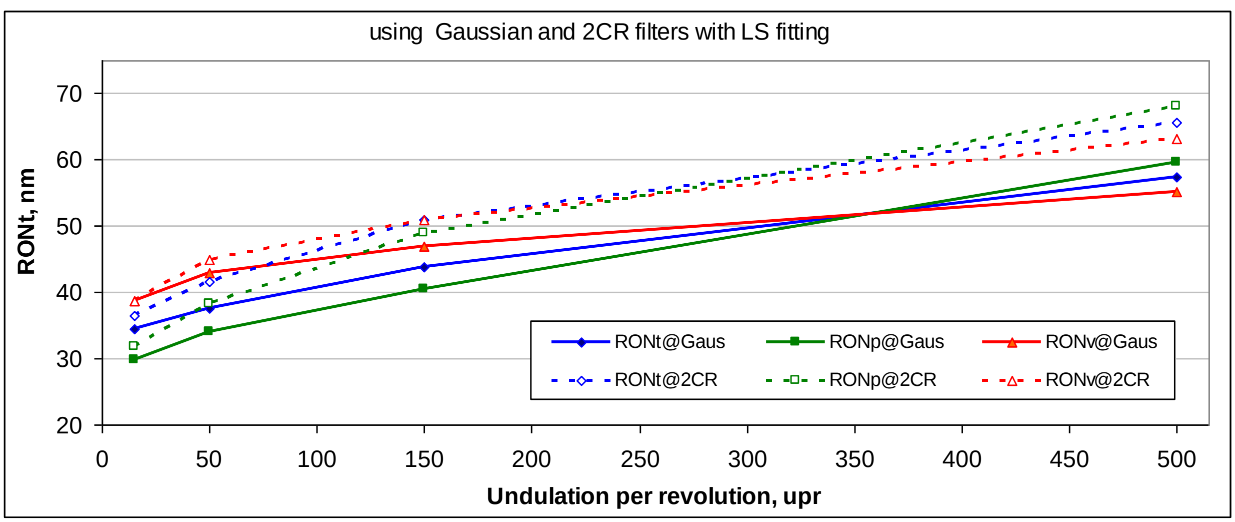


Figure 9. Illustrate the effects spectral wave number on the deviation of RON_t, RON_P and RON_V

VI. UNCERTAINTY ESTIMATION

More reliable analysis to evaluate the proposed experimental method for the influence of fitting filters and reference algorithms on the Talyrond-TR accuracy has been studied. Statistical analysis of roundness error average, standard deviation and combined uncertainty due to repeatability are calculated. Expanded uncertainty for selected ten parameters in measurement has been estimated. The errors averages in roundness measurement results as function of the two fitting filters and four frequency ranges using four reference algorithms are given. The measurement uncertainty mainly results from Talyrond machine, measurement environment and sampling strategies [5, 31 and 34]. While the uncertainty significant contributions include the following parameters:

a. Repeatability

The statistical analysis was carried out in order to evaluate the expanded uncertainty in measurement. The repeatability in measurement has been calculated and evaluated for two fitting filters, four reference algorithms, and four spectral wave numbers, Table 10.

Table 10a: Average, standard deviation and standard uncertainty of RON_t (nm) at 500 Hz

Filter	Gaussian-filter				2CR-filter			
Algorithm	LS	MZ	MC	MI	LS	MZ	MC	MI
	55	48	67	52	63	61	70	68
	55	47	66	51	63	61	69	67
	54	48	66	51	63	61	70	68
	55	48	67	52	64	61	71	69
	55	48	67	52	63	60	70	68
Average	54.8	47.8	66.6	51.6	63.2	60.8	70.0	68.0
SD	0.40	0.40	0.49	0.49	0.40	0.40	0.63	0.63
u_1=SD/√n	0.180	0.179	0.220	0.220	0.179	0.180	0.280	0.283

Table 10b: Average, standard deviation and standard uncertainty of RON_t (nm) at 150 Hz

Filter	Gaussian-filter				2CR-filter			
Algorithm	LS	MZ	MC	MI	LS	MZ	MC	MI
	42	37	52	38	49	42	59	44
	41	37	52	37	49	41	59	45
	42	36	51	37	49	42	60	44
	42	37	51	38	49	42	59	44
	42	37	52	38	50	42	58	44
Average	41.8	36.8	51.6	37.6	49.2	41.8	59.0	44.2
SD	0.40	0.40	0.49	0.49	0.40	0.40	0.63	0.40
$u_1=SD/\sqrt{n}$	0.180	0.179	0.220	0.220	0.179	0.180	0.280	0.179

Table 10c: Average, standard deviation and standard uncertainty of RON_t (nm) at 50 Hz

Filter	Gaussian-filter				2CR-filter			
Algorithm	LS	MZ	MC	MI	LS	MZ	MC	MI
	36	32	46	37	40	35	49	37
	36	31	45	37	41	35	48	37
	36	32	45	36	40	35	49	38
	35	32	46	36	40	35	51	37
	36	32	46	37	40	34	49	36
Average	35.8	31.8	45.6	36.6	40.2	34.8	49.2	37.0
SD	0.40	0.40	0.49	0.49	0.40	0.40	0.98	0.63
$u_1=SD/\sqrt{n}$	0.180	0.179	0.220	0.220	0.179	0.180	0.440	0.283

Table 10d: Average, standard deviation and standard uncertainty of RON_t (nm) at 15 Hz

Filter	Gaussian-filter				2CR-filter			
Algorithm	LS	MZ	MC	MI	LS	MZ	MC	MI
	33	27	41	27	35	30	43	29
	33	27	40	27	34	30	43	28
	33	27	41	26	35	31	44	29
	32	27	40	27	35	30	42	29
	33	26	41	26	35	30	43	29
Average	32.8	26.8	40.6	26.6	34.8	30.2	43.0	28.8
SD	0.40	0.40	0.49	0.49	0.40	0.40	0.63	0.40
u_1=SD/√n	0.180	0.179	0.220	0.220	0.179	0.180	0.280	0.179

The type (A) uncertainty (u_1) values of 0.18, 0.18, 0.22 and 0.22 nm at using LS, MZ, MC, and MI reference algorithms with Gaussian-filter, while the values of 0.18, 0.18, 0.28, and 0.28 nm at using LS, MZ, MC, and MI algorithms with 2CR-filter respectively, as shown in Table 10 (a, b, c, and d). The reference algorithms (MC and MI) have the highest repeatability value (u_1) of 0.28 nm at 2CR-filter.

b. Resolution

The resolution *r* of the used Talyrond machine in last digit of a measured value is causing an uncertainty component u_2:

$$u_2 = r/(2\sqrt{3}) = 1/(2\sqrt{3}) = 0.3 \text{ nm}$$

c. Indication error

The maximum permissible error of indication is 5 nm. When a normal distribution is assumed, the uncertainty component is:

$$u_3 = 5/\sqrt{3} = 2.9 \text{ nm}$$

d. Temperature

The standard reference temperature for measurement is 20 ^{o}C. During the implementation, the environmental temperature in the coordinate metrology laboratory at NIS was controlled within 20±0.5 ^{o}C, the uncertainty component u_4 from temperature and dirt is estimated 0.5 nm.

Above components are all uncorrelated, so the uncertainties of measured points for roundness variation are calculated as follows:

$$u_c = \sqrt{u_1^2 + u_2^2 + u_3^2 + u_4^2} \qquad U_{Exp} = K(u_c)$$

The expanded uncertainty estimation reflects confidence in the high credibility and stability of the proposed method as shown in Table 11.

Table 11: Uncertainty budget in roundness deviation measurement

Fitting filters	Gaussian-filter				2CR-filter			
Fitting algorithms	LS	MZ	MC	MI	LS	MZ	MC	MI
Combined St. uncertainty, u_c	2.96	2.96	2.97	2.97	2.96	2.96	2.97	2.96
Expanded uncertainty, U_{Exp}	5.93	5.93	5.93	5.93	5.93	5.93	5.94	5.93
Average of U_{Exp}	5.93							

VII. CONCLUSIONS

New experimental program has been verified and investigated to establish geometrical data sets aim to reach the lowest deviation with using RTH Talyrond-TR 73 HPR instrument. This program is done and examined to achieve suitable performance evaluation method in roundness measurement at NIS. The proposed methodology of ten metrological parameters have been studied and discussed in detail. Investigated results showed that the high relative deviation in roundness metrology could be attributed to the selected measurement strategies. This is an important validation task especially in traceability chain achievement in NMIs. Consequently, the following conclusions were reached:

1) There are deviation differences of roundness metrology in the same detecting circle of artefact; this is due to the software filter design, reference algorithm, and frequency range which have difference responses according to their design within the maximum permissible error.
2) The deviation in the roundness measurement increases with increasing the spectral wave numbers (upr) when using different types of fitting filters. This is due to the response impact and design of the used filter.
3) The lowest deviation in roundness measurement is achieved when using Gaussian-filter rather than 2CR-filter. Of course, any of both filters gives better measurement response than the case of unfiltered.
4) Lowest rate in roundness deviation is achieved when using MZ reference algorithm. The MC algorithm gives better result than using or MI algorithm.
5) There is great variation in the roundness up to twice times at different measurement parameters when using spectral wave numbers from 1-15 or from 1-500 upr.
6) The expanded uncertainty in roundness measurement is archived within the range of ±5.9 nm. The result of this estimation is confirmed the procedures integrity for the proposed evaluation method.
7) Experimental result shows that the proposed evaluation method based on region division is reliable and effective.

Eventually, the optimal measurement strategy is achieved using Gaussian software filter, MZ reference algorithm at spectral wave numbers of 1-15 for Talyrond-TR 73 HPR ultra-high sensitive machine. Result clearly helps the metrologest to realize and confirm that the touch-sensitive Talyrond-TR 73 HPR tester as an ultra-high accurate and precise machine is powerful tool for NMIs traceability in roundness nanometrology. Moreover, result helps the software engineer to develop new version to be more accurate and precise machine in coordinate nanometrology.

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