Critical evaluation of key data analysis steps in roundness measurements

Krytyczna ocena kluczowych etapów analizy danych w metrologii okrągłości

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Analysis of roundness measurement data is fundamental for the assessment of geometric characteristics of cylindrical and spherical objects. This process comprises four essential stages: modelling, filtering, parameterization, and uncertainty budget estimation. The present work focuses on the first three stages, investigating in detail the influence of selected factors and parameters on the final measurement result. Commonly applied assumptions in roundness metrology were also subjected to verification. Research findings confirm, inter alia, that differences in amplitude roundness parameters can reach up to 50% depending on the adopted reference element (circle). Furthermore, a positive influence of applying a Gaussian filter with a broader bandwidth on amplitude parameters was observed, and the effectiveness of utilising the Fourier transform in roundness profile analysis was confirmed.
KEYWORDS: reference circles, filtering, roundness parameters

Analiza danych pomiarowych okrągłości ma kluczowe znaczenie w ocenie cech geometrycznych obiektów cylindrycznych i sferycznych. Proces ten składa się z czterech podstawowych etapów: modelowania, filtrowania, parametryzacji oraz szacowania budżetu niepewności. W artykule skoncentrowano się na pierwszych trzech etapach, dogłębnie analizując wpływ wybranych czynników i parametrów na końcowy wynik pomiaru. Zweryfikowano również powszechnie przyjmowane założenia stosowane w metrologii okrągłości. Wyniki badań potwierdzają między innymi, iż różnice w amplitudowych parametrach okrągłości mogą dochodzić do 50% w zależności od zastosowanego elementu odniesienia. Co więcej, zaobserwowano pozytywną korelację zastosowania filtru Gaussa o szerszym paśmie przepustowości na parametry amplitudowe, jak również potwierdzono skuteczność wykorzystania transformaty Fouriera w analizie profilu okrągłości.
SŁOWA KLUCZOWE: okręgi odniesienia, filtrowanie, parametry okrągłości

Introduction

The assessment of roundness is of considerable significance in mechanical engineering, particularly within the transportation sector, where the transformation of rotational motion into linear displacement is frequently encountered. For critical components like bearings, pistons, and crankshafts, geometric accuracy directly impacts the operational efficiency and safety of numerous vehicles and machines. Therefore, ensuring high standards in the manufacturing of these circular parts is paramount.

This paper outlines a structured methodology for roundness data analysis, partitioning the process into four primary stages: modelling, filtering, parameterization, and uncertainty budget evaluation. Each stage entails crucial decisions that shape the final measurement result. By analysing these decision points from both theoretical and practical perspectives, this study elucidates their influence on the accuracy and reliability of roundness assessments.

Moreover, the consolidation of roundness analysis techniques and expertise into a unified resource offers substantial benefits for instructional and training purposes, fostering improved understanding for students and practitioners equally. This research also contributes to a doctoral thesis focused on establishing roundness measurement infrastructure at the Świętokrzyski Laboratory Campus of the Central Office of Measures (GUM) in Kielce, highlighting its direct practical relevance and utility.

Modelling

The analysis of roundness measurement data can be structured into four distinct phases: modelling, filtering, parameterization, and uncertainty budget estimation. This framework, as outlined by Raya and Muralikrishnan [1] in their monograph, emphasizes that critical decisions made within each phase significantly influence the final measurement outcomes.

A fundamental step in quantifying roundness deviation involves establishing a reference circle, which serves as the nominal geometry against which measured data points are evaluated. Four principal types of reference circles are conventionally employed in roundness metrology:

- Maximum Inscribed Circle (MICi): The largest possible diameter circle that can be fully contained within the measured profile.
- Minimum Circumscribed Circle (MCCi): The smallest possible diameter circle that entirely encompasses the measured profile.

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- Least-Squares Reference Circle (LSCi): The unique circle determined such that the sum of the squared radial distances from each measurement point to the circle is minimized.
- Minimum Zone Circles (MZCi): A pair of concentric circles, positioned to have the minimum possible radial separation while fully enclosing the measured profile between them.

Various methodologies for computing these reference circles are documented in the literature, with examples provided by Fanwu et al., Liu et al., Yao et al., and Zhi-Min et al. [2-5]. Notably, the LSCi is unique among these four in that it can be determined using a direct, closed-form analytical solution, whereas the computation of MICi, MCCi, and MZCi typically requires iterative algorithms.

The choice of reference circle directly impacts the calculated roundness parameters, such as the total roundness deviation (RONt). Theoretically, the variation in a specific roundness parameter derived using different reference circles should not exceed 100%. However, established practice within roundness metrology, as suggested by Adamczak [6], indicates that this difference typically remains below 50%.

To empirically investigate this commonly accepted 50% threshold, a series of six measurements was conducted using a Hommel-Etamic Roundscan 535 roundness measurement instrument. The objects under test included a steel cylinder (measured at two distinct cross-sections), a steel ring (outer diameter, also measured at two cross-sections), a glass hemisphere, and a ceramic sphere. The resulting total roundness (RONt) values obtained for each reference circle type, along with the maximum observed ratio between these RONt values within each measurement set, are presented in table I.

TABLE I. Experimental results showing calculated RONt values and the maximum RONt/RONt ratio for different reference circles across various measured objects.
TABELA I. Wyniki eksperymentalne pomiarów odchyłki okrągłości RONt i wartości maksymalnej proporcji RONt/RONt dla różnych okręgów odniesienia.

No	RONt LSCi [µm]	RONt MCCi [µm]	RONt MICi [µm]	RONt MZCi [µm]	Max. RONt/RONt ratio
1	3,20	3,74	2,68	2,64	1,41
2	2,67	2,75	2,79	2,75	1,04
3	3,92	3,85	3,44	4,13	1,20
4	4,07	4,41	3,89	4,01	1,13
5	1,29	1,34	1,17	1,24	1,15
6	1,76	1,88	1,60	1,61	1,18

Filtering

Raw roundness measurement data are frequently affected to noise and random errors. To facilitate interpretation, enhance relevant geometrical features, and mitigate unwanted signal components, various filtering techniques are employed. Prevalent examples include 2RC, Gaussian, morphological, and B-spline filters, as discussed by Podulka [7] and standardized within the ISO 16610 series. Among these, Gaussian filtering represents the most widely adopted method in roundness metrology.

The characteristics of a Gaussian filter are typically defined by its harmonic cutoff values, often expressed as undulations per revolution (UPR), such as 1–15 UPR, 1–50 UPR, or 1–150 UPR. These values delineate the frequency band of harmonics that pass through the filter with minimal attenuation, whereas frequencies outside this band experience significant reduction (usually 50% attenuation at the cutoff frequencies themselves, increasing further away from the band). This selective frequency response allows for the exclusion of undesired components, thereby rendering the primary geometrical features within the measured profile more distinct.

To illustrate the impact of filter parameter selection on the resulting roundness profile, measurements were performed on a steel cylinder using the Hommel Etamic Roundscan 535 instrument designated for the Świętokrzyski Laboratory Campus of the Central Office of Measures (GUM).

As shown in fig. 1, extending the filter's harmonic range (e.g., from 1–15 UPR to 1–150 UPR) results in an increased total roundness deviation (RONt).

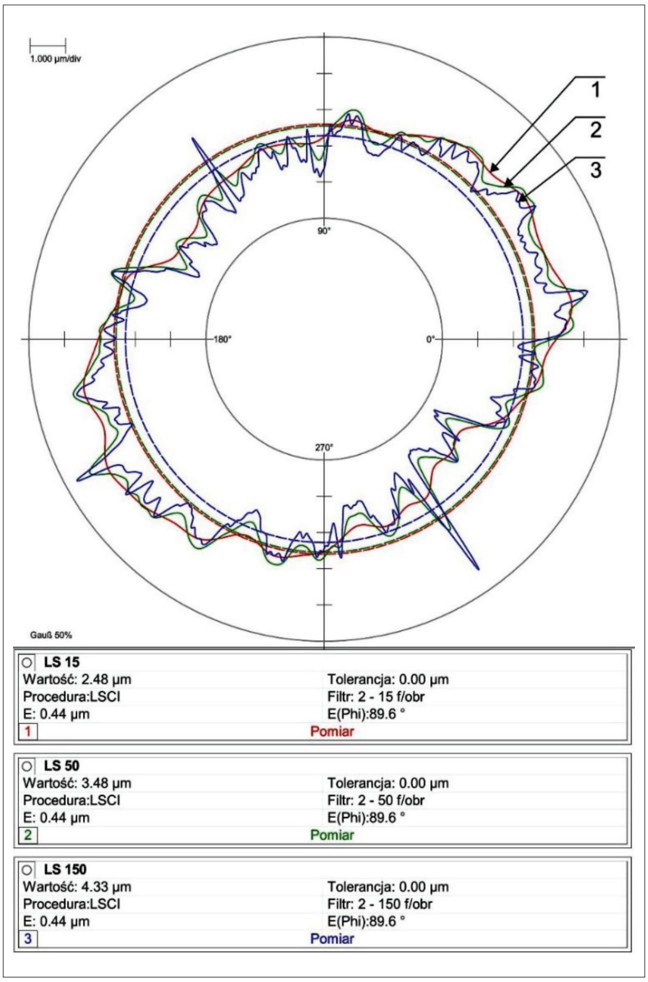

Fig. 1. Comparison of a steel cylinder's roundness profile filtered using Gaussian filters with different harmonic cutoff ranges: (1) 1–15 UPR, (2) 1–50 UPR, (3) 1–150 UPR.
Rys. 1. Porównanie profilu okrągłości stalowego walca z użyciem filtru Gaussa dla różnych wartości cut-off: (1) 1-15 UPR, (2) 1-50 UPR, (3) 1-150 UPR

This phenomenon occurs because narrower filters restrict the superposition of multiple harmonic extrema, effectively removing higher-frequency form deviations. Conversely, when a broader filter bandwidth is applied, extreme peaks or valleys associated with low-, medium-, and high-order harmonics can coincide spatially, leading to larger calculated deviations as more form features are included. For example, the profile exhibits a confluence of harmonic peaks near 210° and overlapping valleys around 330°; these features are markedly more pronounced when applying the 1–150 UPR filter compared to the 1–15 UPR filter.

Unlike the selection of a reference circle, where the effect on the final measurement value might be quantified more directly, the choice of filter must be carefully tailored to the specific geometric characteristics of the object under evaluation. Furthermore, it is crucial to mitigate the influence of the first harmonic component, as this typically corresponds to measurement eccentricity–resulting from misalignment between the workpiece axis and the instrument's axis of rotation–rather than the intrinsic form of the object. Table II provides guidance on selecting appropriate filtering methods based on specific metrological requirements.

Parameterization

The selection of appropriate roundness parameters is essential for guaranteeing that measurements meet the specific functional requirements of a given component. While numerous parameters established in linear profilometry are applicable to roundness metrology due to shared definitions documented in the literature, certain parameters are specific to circular geometries. Among these is *lobing*, which refers to the predominance of a particular low-order harmonic within the roundness profile. For instance, a workpiece exhibiting a dominant fourth harmonic is described as having four lobes.

This parameter holds considerable engineering significance owing to its influence upon the operational integrity of various components. Bearings characterized by pronounced low-order lobing, for example, tend to operate less efficiently, generate increased dynamic loads and noise levels, and exhibit accelerated wear patterns. Similarly, components requiring precise sealing, such as tight-fitting piston-cylinder assemblies, often have stringent specifications regarding low lobing parameters. Although lobing can be inferred through indirect methods (e.g., high-spot count, zero-crossing density, average wavelength), the most rigorous and dependable evaluation techniques entail deconstructing the profile into its constituent harmonics for analysis. This decomposition permits direct comparison of harmonic amplitudes or subsequent processing, such as calculating the Power Spectral Density (PSD) to understand variance distribution across frequencies. Consequently, a thorough comprehension of the Fourier transform, the fundamental tool for such profile deconstruction, is indispensable.

Based on Fourier theory, a roundness profile, R(φ), can be represented as the superposition of sinusoidal (cosine) functions possessing distinct frequencies (harmonics), amplitudes, and phase shifts:

$$R(\varphi) = R_0 + \sum_{n=1}^{k} C_n \cos n(\varphi - \varphi_n)$$

where:
R_0 – is the mean radius,
C_n – is the amplitude of the n-th harmonic,
φ_n – is the phase shift of the n-th harmonic,
k – is the highest harmonic considered.

This mathematical representation facilitates the straightforward identification of the harmonic component with the greatest amplitude. In practical assessments of lobing, the analysis typically encompasses the first 15 harmonics.

To evaluate the practical utility of the Fourier transform in roundness measurement, dedicated software employing the Fast Fourier Transform

Table II. Overview of different filtering methods with recommended applications, benefits, and limitations.
Tabela II. Zestawienie różnych metod filtrowania z uwzględnieniem zalecanych zastosowań, zalet oraz ograniczeń.

Filter	Recommended Use	Benefits	Limitations
Gaussian	Smooth separation of waviness, roughness, form error (optical, typical assess.)	Smooth transition between components, ISO-compliant	Unable to determine sharp cut-off frequency
B-spline	Profiles with sharp changes (damaged surfaces, deformed sealing edges, etc.)	Flexible adaptation to the profile	May affect high-frequency components
2RC	Simple filtering needed (real-time monitoring, vibration analysis, process ctrl)	Easy implementation	Phase shift, low precision
Morphological	Sharp edges, local defects (scratches, dents, pits, tool markings)	Does not blur edges, effective in damage detection	Does not separate frequency components, complex proc.

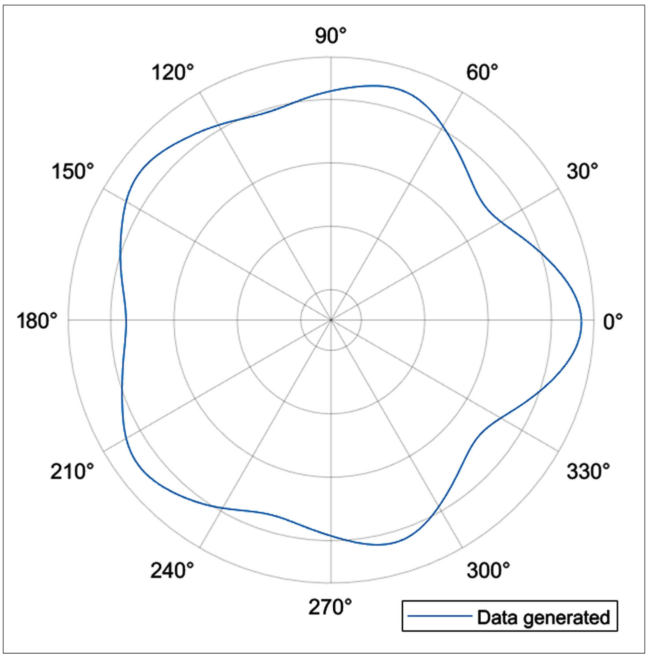

Fig. 2. The plot representing the simulated profile
Rys. 2. Wykres prezentujący wygenerowany profil.

(FFT) algorithm was created to determine harmonic amplitudes from a given profile. Due to limitations in exporting raw measurement data from the available instrument (Hommel-Etamic Roundscan 535), a simulated roundness profile was generated within the MATLAB environment using predefined harmonic amplitudes.

Within this simulation, the fifth harmonic was assigned the largest amplitude (3.00 µm), deliberately creating a profile with a distinct five-lobed characteristic.

Subsequently, the harmonic amplitudes were extracted from this simulated profile utilizing the newly developed FFT-based program. Table III presents a comparison between the original, prescribed amplitudes and those derived computationally via the FFT analysis.

As indicated in table IV, the computationally retrieved amplitudes demonstrate strong agreement with their predefined values. This result validates the application of the Fourier transform (specifically, the FFT algorithm) for quantitative analysis of roundness profiles. This methodology offers a precise and objective means to identify lobing and other harmonic-related geometric features, thereby enhancing the characterization and understanding of the measured object's form.

Results and discussion

Effective roundness analysis necessitates several critical decisions regarding the measurement procedure, which must be customized according to the specific application, the geometric characteristics of the specimen, and the parameters of interest. This investigation revisited several established principles within roundness measurement through practical examination. Firstly, the observed variation in roundness parameters resulting from the use of different reference circles did not exceed 50%, corroborating widely accepted metrological conventions. Secondly, the findings affirmed that the bandwidth selection for Gaussian filtering significantly influences amplitude parameters, such as RONt. Finally, based on the simulations presented herein, the application of the Fast Fourier Transform (FFT) for profile decomposition and analysis was demonstrated to be both viable and advantageous.

Conclusions

This paper presents a contemporary perspective on tools, methodologies, and practices that, despite being widely employed in roundness metrology, have received limited dedicated research attention. It serves as a validation of these procedures, aiming to reinforce their perceived reliability. The principal conclusions derived from this study are enumerated as follows:

- the selection of the reference circle can alter the final calculated roundness parameter value by as much as 50%.
- the type of reference circle employed should be determined based on the intended functional application of the measured object.
- harmonic amplitudes derived using the FFT algorithm exhibit close agreement with the primary roundness deviation profile (quantified difference typically not exceeding 5%), thereby confirming FFT's validity as a robust tool for roundness analysis.
- a correlation exists between the bandwidth of the applied Gaussian filter and the resulting RONt parameter; however, precise quantification of this relationship presents challenges, although the underlying reasons for this correlation have been discussed.

These findings possess tangible implications for various industrial sectors. The bearing industry, for instance, can leverage the confirmed efficacy of

Table III. Comparison of prescribed harmonic amplitudes and amplitudes computed from the simulated profile using FFT.
Tabela III. Porównanie założonych amplitud poszczególnych harmonicznych oraz amplitudy tego samego profilu wyliczone z użyciem algorytmu FFT.

No. harmonic	1	3	4	5	6	10	15
Amplitude [µm]	1.00	1.20	0.70	3.00	0.40	0.07	0.11
Derived amplitude after FFT transformation [µm]	1.02	1.24	0.73	3.07	0.40	0.07	0.11

FFT-based tools for roundness analysis, especially in detecting detrimental lobing phenomena. Furthermore, this work underscores the critical necessity for clearly defined standards regarding roundness parameter selection tailored to specific applications. Inconsistencies in choosing the reference circle and the evaluated parameter can substantially affect the outcomes and subsequent interpretations. Table II, presented earlier in the study, offers valuable guidance for selecting appropriate filtering methods according to specific metrological needs.

It is essential to recognize that the objective of this paper was to furnish a comprehensive overview of the roundness profile analysis process, rather than to conduct formal hypothesis testing concerning common metrological assumptions. Rigorous verification of such hypotheses necessitates further investigation employing methodologies specifically designed for each case. The authors acknowledge the study's limitations, particularly that most experimental aspects would benefit from a larger dataset. Such detailed verification constitutes a significant component of ongoing doctoral research, which includes the implementation of a new roundness measurement system at the Świętokrzyski Laboratory Campus of the Central Office of Measures (GUM). The measurement strategies and procedures developed within that context are poised to benefit considerably from insights gained through future, more extensive investigations.

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