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SIMPLE UNCERTAINTY EVALUATION METHOD FOR ROUGHNESS PARAMETERS MEASUREMENTS BASED ON USE OF MONTE CARLO METHOD

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Abstract: In this paper a simple uncertainty evaluation method for roughness parameters measurements is presented. It is based on the Monte Carlo method, described in the supplement to "Guide to the expression of uncertainty in measurement" (GUM). The Monte Carlo method is an advanced numerical approach that takes into account the complexity of the measurement system through random simulations. Instead of making simple statistical assumptions, Monte Carlo generates a large number of random input data samples that represent different possible values of the input values in the system. The measurement model describing the relationship between the input values and the measurement result has to be built and it may account for different contributors. In this paper we present the method that is used to simulate the influence of sources such as repeatability, calibration results and probe errors. Thanks to numerical simulations on which this method is based, it is possible to increase the number of analysed measurement results from 50 to 100 000 and perform on this basis the determination of uncertainty of considered roughness parameter measurement.

Key words: surface topography, roughness, uncertainty, Monte Carlo Method.

1. INTRODUCTION

Surface roughness measurement constitutes a critical stage in the quality control of manufactured components, as surface finish quality significantly affects the operational performance of a part as well as its physical properties [1,2]. Moreover, roughness measurements can provide valuable insights into the condition of the manufacturing tool [3,4].

A variety of methods are available for measuring surface roughness, which can be broadly categorized into contact techniques and non-contact approaches such as confocal microscopy, white light interferometry, or focus variation microscopy [5,6]. The choice of

measurement method, which largely depends on the intended application, can substantially influence the accuracy and reliability of the results [7].

In particular, contact-based methods have been the subject of extensive research. As outlined by Pawlus et al. in [8], the main sources of errors in surface roughness measurements can be attributed to the measuring instrument, the software employed, the characteristics of the measured object, and the environmental conditions under which the measurement is performed.

One notable error source of profilometric methods is the mechanical filtering of surface features by the stylus tip. As discussed in [9], the

geometry and size of the stylus significantly affect the measured roughness parameters as well as the resulting power spectral density function. Another factor influencing the results of profilometric surface roughness measurements is the scanning speed. This issue was examined, among others, in [10], where a general trend was observed: as scanning speed increases, amplitude parameters tend to be underestimated, while spacing parameters show an increasing tendency. In [11], the impact of various post-processing techniques and profile leveling methods on roughness measurement outcomes was investigated. The authors found that depending on the applied procedures surface levelling, surface roughness values may be underestimated by as much as 30%.

A separate and complex issue concerns the estimation of measurement uncertainty in contact profilometry. The large number of factors influencing the measurement process complicates reliable uncertainty quantification. Procedures for estimating uncertainty in contact profilometer measurements have been outlined in [12,13]. According to these studies, the principal sources of uncertainty include calibration errors in the profilometer's movement axes (primarily Z but also X), sensor noise, the applied probing force, and the characteristics of the filtering process. In [13], the analysis also accounted for the instrument's repeatability and the influence of the measured object, specifically through an assessment of variability in measurement results collected from different areas of the surface.

An example implementation of an uncertainty estimation procedure was also described in [14]. Considerations presented there include also calibration factor understood as the ratio between the step height measured by the instrument and the certified value provided for the calibration standard. The proposed method of uncertainty estimation was shown to be effective for parameters based on single-point values extracted from the observed profile; however, the author emphasized the difficulty in extending this approach to more complex parameters, such as R_a .

An alternative approach was presented in [15,16], where Type A evaluation methods were employed to estimate uncertainty. This method

requires multiple repetitions of the measurement sequence for each evaluation, and its applicability is limited by the need to meet several conditions, for example, the assumption of a symmetric distribution of the resulting values.

This paper presents an attempt to develop a simulation-based method for estimating measurement uncertainty using the Monte Carlo approach. Implementing uncertainty simulation methods for measurement systems is often a nontrivial task [17]; however, such models have been successfully applied in case of entire measurement systems—such as coordinate measuring machines (CMMs) [18]—as well as to individual system components [19].

The primary advantage of this approach lies in its ability to simulate thousands of measurement outcomes, each incorporating variability stemming from fundamental sources of uncertainty. Benefits of such approach include acceleration of accuracy assessment and simplification of accuracy evaluation procedure from user perspective. The last of mentioned advantages is maybe even more important as uncertainty estimation in case of roughness measurements is complex task [14].

The study presented in the following parts of the paper outlines the model used for the simulations and describes the validation procedure applied to assess its reliability. Additionally, the results obtained using the proposed method are presented for various surfaces examples.

2. DEVELOPED SIMULATION METHOD FOR ROUGHNESS UNCERTAINTY ESTIMATION

The Monte Carlo method, as described in the extension of the GUM-S1 standard [20], is an advanced numerical approach that accounts for the complexity of the measurement system through random simulations. Rather than relying on simple statistical assumptions, Monte Carlo generates a large number of random input samples that represent various possible values of the input variables in the system.

The Monte Carlo method offers several key advantages over Method A. It allows for the inclusion of various sources of disturbances with

arbitrary probability distributions (e.g., normal, uniform), handles nonlinear relationships within the measurement system, and provides greater flexibility in analyzing complex setups. In this study, the Monte Carlo method was used because it enables the consideration of error sources such as repeatability, calibration influence, or probe error. Additionally, it produces results based on a large number of simulations, allowing for accurate estimation of measurement uncertainty.

While Method A may be faster—since it does not require preliminary studies to determine the probability distributions assigned to individual sources of uncertainty—it is limited to simple cases and data that follow a normal distribution.

The measurement model developed to describe the relationship between the input variables and the roughness measurement result can be given with equation (1):

$$x_s = R_{x_s} + e_{cal} + e_{rep} + e_{tp} \quad (1)$$

where:

R_{x_s} - simulated value of the evaluated surface roughness parameter

e_{cal} - error associated with the influence of device calibration

e_{rep} - error related to surface uniformity and measurement reproducibility

e_{tp} - error resulting from the characteristics of the transducer used in the profilometer

Before the developed method can be applied in practice, the distributions describing the influence of individual uncertainty sources on the measurement result must be determined experimentally. It is assumed that each factor firstly should be checked for normality.

The most important parameter from the model's perspective is the first component, whose distribution is determined based on 50 surface roughness measurements taken at the same location on the sample (only for Monte Carlo method preparation – distribution parameters can be transfer for samples of similar properties).

The second component e_{cal} reflects the influence of device calibration and can be estimated by repeatedly measuring the calibration standard used in the calibration process.

The third component e_{rep} indicates how the measurement result may be affected by changing the location of the measurement. It can be determined by repeatedly measuring the same sample at several different positions (a recommended number is five different cross-sections).

The last component e_{tp} primarily accounts for the noise of the sensor responsible for measurements along the z-axis of the device. It can be estimated by repeatedly measuring a special flatness standard (e.g., a dedicated glass standard) at the same location.

Naturally, the preliminary studies required to obtain input data for the model involve a certain time investment (due to repeated measurements) and financial cost (acquisition of standards necessary for the tests). However, it should be noted that some of these studies can be performed less frequently and independently of the sample (i.e., components related to calibration influence and sensor noise), while others, although requiring multiple repetitions, allow for uncertainty estimation after a single measurement once the input data has been obtained.

After assessing distribution and parameters that describes it for each factor, the simulation of multiple measurement results are carried out 100 000 times to obtain measurement uncertainty calculated according to [20].

3. MODEL VALIDATION AND ITS APPLICATION FOR ROUGHNESS UNCERTAINTY ESTIMATION

Model validation was carried out by comparing the results produced by the model for a surface roughness standard with the uncertainty specified in its certificate (Fig. 1), followed by verifying whether the uncertainty ranges have a common intersection.

All experiments described in this paper were conducted using the Taylor Hobson Form Talysurf i-Series profilometer. The instrument is housed in a specialized room with controlled environmental conditions to ensure high measurement accuracy ($20^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$).



Fig. 1 Taylor Hobson Form Talysurf i-Series profilometer during measurements of Ra standard used in validation of developed simulation method of estimation of uncertainty of roughness measurements

The instrument is placed within a custom-built enclosure, constructed from aluminum profiles and Plexiglas panels. This additional enclosure serves to isolate the instrument from external environmental disturbances, such as air currents or dust particles, which could interfere with the fine measurements. Furthermore, the profilometer is mounted on a vibration-dampening system and foundation, which is structurally isolates it from the rest of the building to further reduce the impact of ambient vibrations.

The reference standard was measured following the procedures outlined in [21]. The comparison results are shown in Fig. 2.

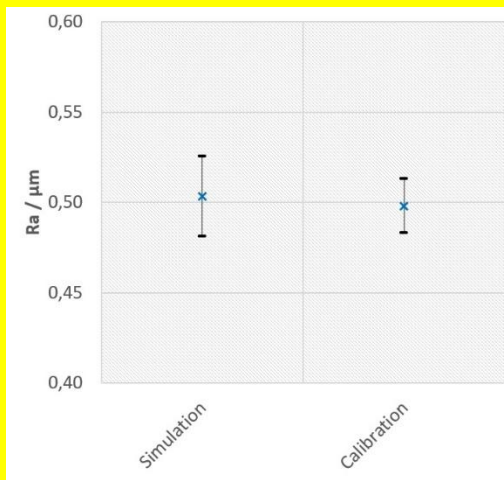


Fig. 2 Comparison of surface roughness measurement results with the data obtained from the calibration of the reference object. The error bars represent the values of the expanded uncertainty U , estimated using a coverage factor $k=2$.

As can be observed, both Ra values are very close to each other, and the uncertainty intervals show high consistency. It should be also noted that the uncertainty obtained directly from the 50 repeated measurements of the standard using the Type A evaluation method would amount to

only 0.1 nm—making it 100 times smaller than the value stated in the calibration certificate.

To assess the usefulness of the developed uncertainty estimation method, a series of measurements was carried out on a surface roughness testing object. The calibration artifact is shown in Fig. 3. The presented standard consists of various reference elements made from different materials in a variety of shapes.

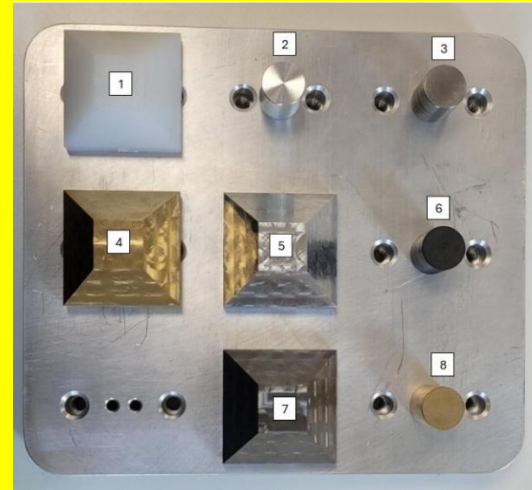


Fig. 3 Standard which incorporates different samples for roughness measurement: 1 – trapezoid made from polyamide; 2 – cylinder made form aluminium; 3 – cylinder made of steel; 4 – trapezoid made of brass; 5 – trapezoid made of aluminium; 6 – cylinder made of polyamide; 7 – trapezoid made of steel; 8 – cylinder made of brass

All measurements on the samples were performed in accordance with the guidelines provided in [21]. Table 1 presents the determined values of the Ra and Rz parameters for each reference standard, along with the uncertainty estimated using the developed simulation-based method.

Table 1. Values of the Ra and Rz parameters along with the corresponding expanded uncertainty values (coverage factor $k=2$). All values are given in micrometers μm .

Art. no.	Ra	U_{Ra}	Rz	U_{Rz}
1	4,273	0,050	29,548	0,082
2	1,340	0,048	10,379	0,091
3	0,701	0,051	3,517	0,054
4	1,118	0,047	7,630	0,057
5	1,031	0,051	7,270	0,060
6	0,746	0,050	4,114	0,052
7	0,500	0,049	2,864	0,049
8	0,342	0,051	2,265	0,050

4. CONCLUSIONS

This paper presented a practical method for estimating uncertainty in roughness measurements using the Monte Carlo approach. The model accounts for major uncertainty contributors, including calibration, repeatability, surface variability, and probe noise. By simulating 100 000 measurement results, it enables robust and comprehensive uncertainty estimation.

Validation with certified standards confirmed the method's accuracy, showing good agreement with reference data. The model also proved effective across various surface types and materials.

Although initial input data preparation requires time and resources, some elements can be reused, and once configured, the model allows uncertainty estimation from a single measurement. Compared to traditional Type A methods, the Monte Carlo approach offers better adaptability to complex measurement scenarios and improves both accuracy and usability in roughness evaluation.

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6. REFERENCES

- [1] D.J. Whitehouse, Surface Characterization and Roughness Measurement in Engineering, in: Photomechanics, P.K. Rastogi (Ed.), Springer-Verlag, ISSN 1437-0859, Berlin, 2000.
- [2] D.J. Whitehouse, Handbook of Surface and Nanometrology, CRC Press, ISBN 9781420082012, Boca Raton, 2011.
- [3] M. Wiczorowski, M. Bigerelle, C. Brown, P. Pawlus, R. Reizer, A. Pereira, Surface Inspection and Description in Metrology and Tribology—Vol.1. Materials 15, ISSN 1996-1944, 2022.
- [4] H. Trumpold, Process related assessment and supervision of surface textures, International Journal of Machine Tools and Manufacture 41, ISSN 1879-2170, 2001.
- [5] R. Leach (Ed.), Characterisation of Areal Surface Texture, Springer, ISBN 978-3-031-59310-9, Cham, 2024.
- [6] R. Leach (Ed.), Optical Measurement of Surface Topography, Springer-Verlag, ISBN 978-3-642-12012-1, Berlin, 2011.
- [7] T.V. Vorburger, H.G. Rhee, T.B. Renegar, J.F. Song, A. Zheng, Comparison of optical and stylus methods for measurement of surface texture, The International Journal of Advanced Manufacturing Technology 33, ISSN 1433-3015, 2007.
- [8] P. Pawlus, R. Reizer, M. Wiczorowski, G.M. Krolczyk, Study of surface texture measurement errors, Measurement 210, ISSN 1873-412X, 2023.
- [9] P. Pawlus, Mechanical filtration of surface profiles, Measurement 35, ISSN 1873-412X, 2004.
- [10] P. Pawlus, M. Śmieszek, The influence of stylus flight on change of surface topography parameters, Precision Engineering 29, ISSN 1873-2372, 2005.
- [11] D. Nečas, M. Valtr, P. Klapetek, How levelling and scan line corrections ruin roughness measurement and how to prevent it, Scientific Reports 10, ISSN 2045-2322, 2020.
- [12] H. Haitjema, Uncertainty Analysis of Roughness Standard Calibration Using Stylus Instruments, Precision Engineering 22, ISSN 1873-2372, 1998.
- [13] S. Zahwi, M. Koura, A. Mekawi, Factors Influencing Uncertainty Evaluation for Surface Roughness Measurements, Proceedings of the XVII IMEKO World Congress, June 2003, Dubrovnik, Croatia.
- [14] R. Leach, The Measurement of Surface Texture using Stylus Instruments, Measurement Good Practice Guide No. 37, ISSN 1368-6550, 2001.
- [15] D. Kubatova, M. Melichar, Uncertainty of Surface Measurement, Proceedings of the 9th DAAAM International Symposium on Intelligent Manufacturing and Automation, October 2018, Zadar, Croatia.

- [16] G. Farkas, A. Dregelyi-Kiss, Measurement uncertainty of surface roughness measurement, IOP Conf. Series: Materials Science and Engineering 448, ISSN 1757-899X, 2018.
- [17] P. Gaška, A. Gaška, M. Gruza, Challenges for Modeling of Five-Axis Coordinate Measuring Systems, Applied Sciences 7, EISSN 2076-3417, 2017.
- [18] P. Gaška, A. Gaška, J. Śladek, J. Jędrzejewski, Simulation model for uncertainty estimation of measurements performed on five-axis measuring systems, International Journal of Advanced Manufacturing Technology 104, EISSN:1433-3015, 2019.
- [19] M. Gruza, A. Gaška, J. Śladek, S. Stojadinovic, V. Majstorovic, P. Gaška, W. Harmatys, Method for Accuracy Assessment of the Length Measurement Unit of Laser Tracking Systems, Applied Sciences 11, EISSN 2076-3417, 2021.
- [20] Supplement 1 to the "Guide to the expression of uncertainty in measurement" – Propagation of distributions using a Monte Carlo method, JCGM 101:2008.
- [21] ISO 4288:1996 Geometrical Product Specifications (GPS) — Surface texture: Profile method — Rules and procedures for the assessment of surface texture, ISO Geneva, Switzerland, 1996.

METODĂ SIMPLĂ DE EVALUARE A INCERTITUDINII PENTRU MĂSURAREA PARAMETRILOR DE RUGOZITATE BAZATĂ PE UTILIZAREA METODEI MONTE CARLO

În această lucrare este prezentată o metodă simplă de evaluare a incertitudinii pentru măsurarea parametrilor de rugozitate. Metoda se bazează pe metoda Monte Carlo, descrisă în suplimentul la „Ghidul pentru exprimarea incertitudinii de măsurare” (GUM). Metoda Monte Carlo este o abordare numerică avansată care ține cont de complexitatea sistemului de măsurare prin simulări aleatorii. În loc să se bazeze pe ipoteze statistice simple, metoda Monte Carlo generează un număr mare de eșantioane de date de intrare aleatorii care reprezintă diferite valori posibile ale variabilelor de intrare din sistem. Este necesară construirea unui model de măsurare care să descrie relația dintre valorile de intrare și rezultatul măsurării, iar acesta poate include diverși contributory. În această lucrare prezentăm metoda utilizată pentru a simula influența unor surse precum repetabilitatea, rezultatele calibrării și erorile sondei. Datorită simulărilor numerice pe care se bazează această metodă, este posibilă creșterea numărului de rezultate de măsurare analizate de la 50 la 100 000 și, pe această bază, determinarea incertitudinii asociate măsurării parametrului de rugozitate analizat.

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