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THREAD INSPECTION USING THE WAVELINE W800R PROFILOMETER: METHODOLOGY FOR METHOD VERIFICATION

The ***subject matter*** *of the study is the thread inspection method using the WAVELINE W800R profilometer and its verification. This includes determining the accuracy parameters of the calibration method and confirming its suitability for practical application. The* ***aim*** *of the work is to investigate and evaluate the suitability of a thread gauge calibration method using the WAVELINE W800R profilometer based on an analysis of measurement precision, reproducibility, and accuracy. The* ***tasks*** *include: the development and application of an evaluation algorithm for the calibration method; determination of key metrological characteristics affecting measurement accuracy; assessment of the method's repeatability and within-laboratory reproducibility; analysis of the method's stability under the influence of various factors; and determination of measurement accuracy using a comparison coefficient. The* ***methods*** *used involve experimental studies of the calibration method's accuracy with the application of statistical tests (Cochran, Grubbs, Fisher, and Student's t-test) to verify variance homogeneity and exclude outliers. Multiple repeated measurements of thread parameters were carried out, along with an analysis of the influence of external factors and a comparison of results using the k-criterion. The* ***results*** *confirmed the feasibility of using the WAVELINE W800R profilometer for high-precision measurement of thread gauges. The method demonstrated sufficient repeatability and within-laboratory reproducibility. The conducted analysis of the method's stability under varying environmental conditions confirmed its robustness. The method passed the accuracy verification using the comparison coefficient and complies with metrological control requirements.* ***Conclusions****: the thread inspection method using the WAVELINE W800R profilometer has proven suitable for laboratory use; it can be implemented in metrological practice for the control of thread gauges. At the same time, it was established that the verification process is time-consuming, which should be considered when organizing calibration activities. It is recommended to perform re-verification of the method after the calibration of reference equipment.*

Keywords: *calibration method verification; WAVELINE W800R profilometer; measurement precision; repeatability and reproducibility; thread inspection.*

Introduction

To assess the suitability of calibration methodologies and to determine the effectiveness of a method, the following procedures or combinations thereof are applied:

- calibration using more accurate reference standards;
- comparison of results obtained through other calibration methodologies;
- interlaboratory comparisons;
- systematic evaluation of factors influencing calibration results;
- evaluation of measurement uncertainty based on scientific understanding of the theoretical principles of the method and practical experience.

The suitability of calibration methodologies is assessed by determining the following characteristics:

- repeatability;
- reproducibility;
- stability and accuracy.

The scope of assessment (selected criteria and evaluation methods) should correspond to the application needs in accordance with customer requirements.

A block diagram of the method verification process is shown in Fig. 1.

During method evaluation, the characteristics of the method and indicators such as repeatability, within-laboratory reproducibility, and measurement accuracy are identified and confirmed.

The results of the suitability assessment of calibration methods according to individual indicators are documented in evaluation reports.

Suitability assessment is always a compromise between cost, risk, and technical capabilities. In many cases, accuracy indicators (e.g., detection limits, selectivity, linearity, repeatability, reproducibility, stability, and cross-sensitivity) may only be presented in a simplified form due to a lack of information.

Let us consider publications that demonstrate the importance of using profilography and other high-precision surface measurement methods for quality control in various industries. In particular, the article by Zhou and Xiang highlights the effectiveness of profilometry for measuring thread parameters, which is crucial for ensuring the reliability of mechanical systems in the aviation and automotive industries [1]. The authors emphasize the advantages of non-contact measurement methods that enable the acquisition of high-precision data without affecting the surface.

In [2], the authors expand on the application of modern high-precision surface measurement methods, stressing the importance of size, geometry, and surface texture parameters in precision and ultraprecision engineering. The publication discusses the necessity of controlling manufacturing processes and the capabilities of surface measurements to ensure the functional characteristics of modern products. In this case, the researchers do not specify the exact application of the studied method, but it can certainly be used for quality control of threaded surfaces in the aviation and mechanical engineering industries.

Related aspects of nanometrology, including the use of profilographs for high-precision surface measurements, can also be found in this book [3].

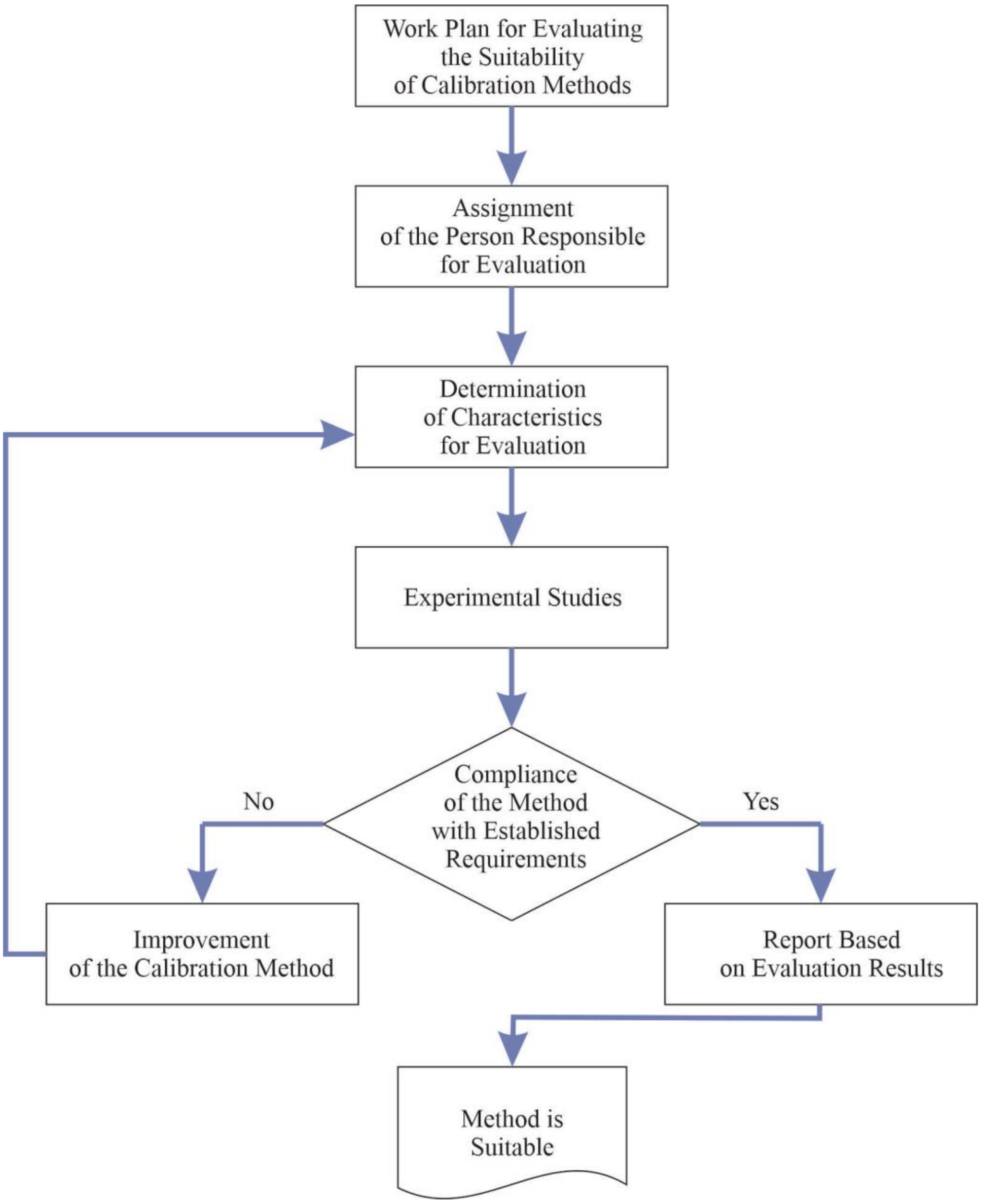

Fig. 1. Block diagram of method verification

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The authors discuss sensors and measurement systems used in nanomanufacturing, emphasizing the importance of precise surface control to ensure product quality. The methods considered can be adapted for accuracy control of threaded connections at the nanoscale level, which is relevant for advanced industrial sectors.

Surface measurement methods are also studied by a group of researchers who presented their findings in this publication [4]. The authors underline the importance of controlling surface geometry and texture to ensure quality, using automotive components as an example. The discussed surface metrology methods can be tailored to specific cases and applied to ensure the reliability and safety not only of vehicles but also of aircraft.

Overall, previous studies provide valuable information on surface control methods that can be used in our research on the application of profilographs, such as the WAVELINE W800R, to ensure the quality and reliability of threaded connections in modern aircraft manufacturing.

1. Theoretical section

Reference standards, the laboratory's measuring instruments (MIs), or MIs submitted for calibration may be used to assess the suitability of a calibration methodology [5]. The evaluation of the suitability of the calibration methodology under assessment is carried out based on experimental data obtained by at least two operators at one of the calibration points under the following conditions:

- each operator repeats the calibration procedure at least 10 times over a short period of time (on the same day) – this constitutes one measurement series for calibration;
- each operator performs at least three such series over a short period of time (on the same day).

The calibration dates for each operator must differ. Additionally, it is preferable that environmental conditions vary (as much as possible).

The procedure for processing the obtained experimental data in order to assess the repeatability, reproducibility, and accuracy of the calibration methodology is outlined below.

Evaluation of precision under repeatability conditions

The assessment of the suitability of the calibration methodology under repeatability conditions is carried out in accordance with section 4.7.1 of DSTU GOST ISO 5725-4 [6].

Repeatability conditions imply:

- the same calibration methodology;
- use of the same equipment under identical conditions;
- involvement of the same operator;
- repetition over a short period of time (on the same day);
- the same reagents (if applicable).

The indicators of repeatability are the standard deviation of the measured values under repeatability conditions and the repeatability limit of the measurement results, which can be justifiably attributed to the calibration methodology.

The assessment of the standard deviation of measurement results under repeatability conditions is carried out as follows:

1) When the verified method is applied $n \cdot (n \geq 5)$ times, n values of the measured quantity y_{li} $(i = 1, 2, ..., n)$ are obtained in each of the $m \cdot (m \geq 3)$ series $(l = 1, 2, ..., m)$.

2) The arithmetic means value $\overline{Y_l}$ of the measured quantity and the variance S_l^2 of the measurement results in series l are calculated using the following formulas:

$$\overline{Y_l} = \frac{\sum_{i=1}^{n} y_{li}}{n} \quad (1)$$

$$S_l^2 = \frac{\sum_{i=1}^{n} (y_{li} - \overline{Y_l})^2}{n-1} \quad (2)$$

3) Possible outliers in the variances are checked using Cochran's criterion [6].

4) If the check using Cochran's criterion raises suspicion that the high variation is caused by only one of the measurement results, the obtained data are analyzed for possible outliers using Grubbs' test [7].

If outliers are found, erroneous results are excluded, and the data are rechecked using Grubbs' test.

The final number of measurement results in each series must be at least five.

5) The standard deviation, which characterizes the closeness of agreement between measurement results, is calculated using the following formula:

$$S_r = \sqrt{\frac{\sum_{k=1}^{m} S_l^2}{1}} \quad (3)$$

Repeatability limit – the value which, with a confidence probability of 95%, does not exceed the absolute difference between the results of any two measurements obtained under repeatability conditions. The repeatability limit is calculated (ISO 5725-6, Section 4.2) using the following formula:

$$r_n = 2.77 \times S_r \quad (4)$$

Suppose the absolute difference between the results of any two measurements obtained under repeatability conditions does not exceed the repeatability limit. In that case, the method is considered suitable for use under repeatability conditions.

Estimation of precision under within-laboratory reproducibility conditions (within-laboratory reproducibility)

Reproducibility conditions include:

– the same (or different, if applicable) calibration method;

– use of the same (or different) equipment under the same conditions;

– involvement of at least two operators;

– calibration performed on different days;

– different reagents (if used).

The indicators of within-laboratory reproducibility are the standard deviation of measurement results obtained under within-laboratory reproducibility conditions, and the within-laboratory reproducibility limit for measurement results.

Reproducibility is evaluated as follows:

1) Based on the experimental data, the arithmetic mean value of the measurement results over l series $\overline{\overline{X}}$, and S_R, are calculated using the following formulas:

$$\overline{\overline{X}} = \frac{\sum_{j=1}^{l} \overline{X_l}}{l} \quad (5)$$

$$S_R = \sqrt{\frac{\sum_{j=1}^{l} (\overline{X}_l - \overline{\overline{X}})^2}{l-1}} \quad (6)$$

2) Possible outliers in the variance are checked using Cochran's criterion [6].

3) If the check using Cochran's criterion raises suspicion that the high variation is caused by only one of the measurement results, the obtained data are analyzed for possible outliers using Grubbs' test [7].

4) If outliers are detected, erroneous results are excluded, and the data are rechecked using Grubbs' test.

The within-laboratory reproducibility limit is the value that, with a confidence probability of 95%, does not exceed the absolute difference between the results of any two measurements obtained under within-laboratory reproducibility conditions.

The within-laboratory reproducibility limit is calculated using the following formula:

$$R = 2.77 \cdot S_R \quad (7)$$

Suppose the absolute difference between the results of any two measurements obtained under within-laboratory reproducibility conditions does not exceed the within-laboratory reproducibility limit. In that case, the method is considered suitable for use under repeatability conditions.

Study of Method Stability

To conduct the study, it is necessary to identify factors that may vary in the laboratory and whose variability can lead to changes in the method's characteristics. Such factors may include: the operator, environmental conditions (e.g., temperature), equipment, and so on.

The method must be tested for stability with respect to the identified factors by comparing the results obtained on the same object under two different (preferably extreme) values of the influencing factor that can occur in the laboratory. These different factors may include different operators, extreme temperatures at which tests may be performed, etc.

The stability check for the corresponding factor(s) is carried out as follows:

– Under different values of the factor(s), $l \geq 5$ (with $l = 10$ recommended) measurement results of the same quantity are obtained under repeatability conditions;

– For each of the two values of the factor, the mean values $\overline{X}_{l1}$, $\overline{X}_{l2}$ and the standard deviations S_{r1}, S_{r2} of the measurement results are calculated;

– The value of the Fisher criterion is calculated using the formula $F = \frac{\max(S_1^2, S_2^2)}{\min(S_1^2, S_2^2)}$ and compared with the critical value of the Fisher criterion $F(0.05;\, k_1;\, k_2)$ for the significance level $\alpha = 0.05$, where $k_1 = k_2 = l-1$ – the degrees of freedom for the larger and smaller variances, respectively;

– If the calculated value of the Fisher criterion exceeds the critical value, the method is considered unstable with respect to the given factor;

– If the calculated value of the Fisher criterion does not exceed the critical value, the Student's t-test is calculated using the formula:

$$t = \frac{|x_1 - x_2|}{\sqrt{S_1^2 + S_2^2}} \quad (8)$$

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– The critical value of Student's t-test $t(0.05;k)$ is determined for a significance level of 0.05, where $k = 2 \cdot l - 2$ is the number of degrees of freedom;

– If the calculated value of Student's t-test exceeds the critical value, the method is considered unstable;

– If the calculated value of Student's t-test does not exceed the critical value, the method is considered stable.

If the method is deemed unstable, the causes of instability must be analyzed and, if possible, eliminated.

Estimation of Method Accuracy

The suitability of calibration methods is evaluated based on the calibration results and the expanded uncertainty of these results using the comparison coefficient k. Confirmation of the suitability of the calibration method is established by fulfilling the following condition:

$$k = \frac{|Y_1 - Y_2|}{\sqrt{U_1^2 + U_2^2}} \leq 1, \quad (9)$$

where k – comparison coefficient;

Y_1 – calibration result obtained with operator 1;

Y_2 – calibration result obtained with operator 2;

U_1 – expanded measurement uncertainty of the calibration result obtained with operator 1;

U_2 – expanded measurement uncertainty of the calibration result obtained with operator 2.

If the verified method is deemed suitable according to all criteria, it is considered suitable for use as a whole.

2. Practical section

As an example of method verification, the calibration control of an M64×6 6H GO thread gauge (Fig. 2) was performed using a Tesa Micro-Hite 3D bridge-type CMM equipped with an HP-L-10.10 Laser Scanning Sensor [8] and a WAVELINE W800R profilometer [9].

During scanning, the recommendations for thread inspection from EURAMET cg-10 [6] were applied, specifically:

– determination of the gauge coordinate system;

– calculation of the nominal point cloud based on the previously defined form element using formula (1), taking into account the coordinates measured in the first stage and the nominal parameters of the helical thread;

– measurement performed on each turn of the helical thread;

– the gauge had been previously calibrated at the NSC "Institute of Metrology", Kharkiv.

As a result of the scanning, a set of points (point cloud) representing the actual profile was obtained.

Based on the thread measurements performed with the WAVELINE W800R profilometer, the values of the thread pitch, flank angle, and mean diameter were obtained. These results were then compared using the *k* criterion calculated according to formula (9). The comparison results are presented in Table 1.

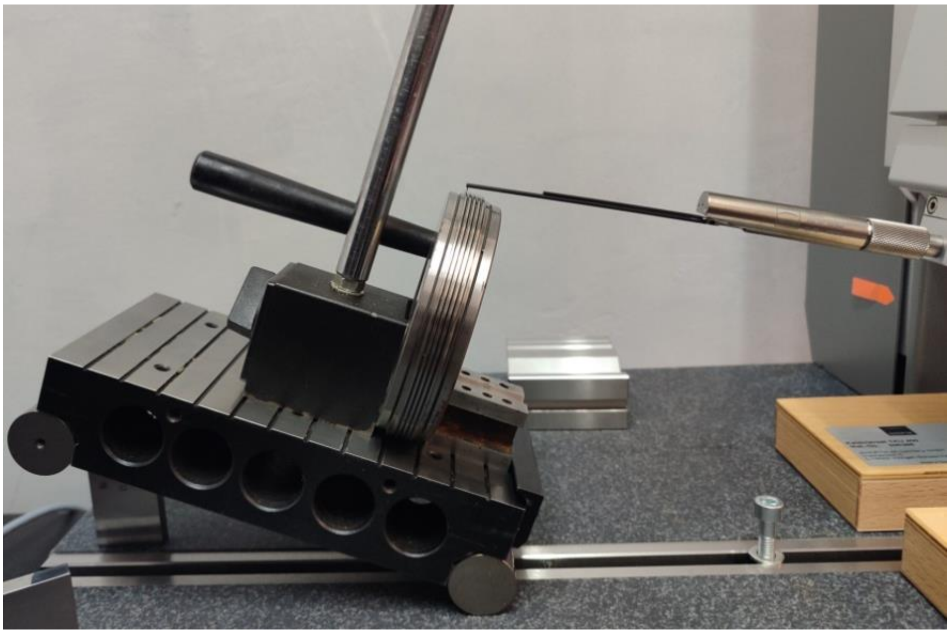

Fig. 2. General View of the Gauge

Table 1

Comparison of Results Using the k Criterion

Pos.	Date	05.12.2023			05.12.2023		
	Operator	Operator 1			Operator 2		
	Indicator name	Series 1	Series 2	Series 3	Series 1	Series 2	Series 3
Y_1	Thread pitch, P, mm	5.996	5.996	5.996	5.996	5.996	5.999
Y_2	Thread pitch, P, mm	5.998	5.998	5.996	6.003	6.004	5.996
Y_3	Thread pitch, P, mm	5.996	5.996	5.996	6.004	5.996	6.002
Y_4	Thread pitch, P, mm	5.998	5.997	5.996	5.998	5.997	6.003
Y_5	Thread pitch, P, mm	5.996	5.996	5.998	6.001	6.003	6.004
Y_6	Thread pitch, P, mm	5.998	5.995	5.998	5.998	5.995	5.996
Y_7	Thread pitch, P, mm	5.998	5.996	5.997	5.998	5.996	5.997
Y_8	Thread pitch, P, mm	5.996	5.998	5.997	5.996	6.003	5.997
Y_9	Thread pitch, P, mm	5.994	5.996	5.996	5.994	6.004	5.996
Y_{10}	Thread pitch, P, mm	5.996	5.996	5.996	5.996	5.996	5.996
Y_{mean}	Arithmetic Mean	5.9966	5.9964	5.9966	5.9984	5.999	5.9986
S_1^2	Variance of measurement results	1.822E-06	9.3333E-07	7.1111E-07	1.0711E-05	1.5333E-05	1.0267E-05

Pos.	Indicator name	Operator 1	Operator 1
Hypothesis testing for equality of sample variances using Cochran's criterion		G=0.5256 (Gcr=0.6168) No variance outlier detected	G=0.4223 (Gcr=0.6168) No variance outlier detected
		G=0.3855 (Gcr=0.3682)	
S_r	Standard deviation of repeatability	0.001074968	0.003479038
r	Repeatability limit	0.002977661	0.009639935
S_R	Standard deviation of reproducibility	0.001186592	
R	Reproducibility limit	0.003286859	
Conclusion on precision based on repeatability assessment			
Conclusion on the precision of the methodology based on the reproducibility assessment		The methodology is stable to factor(s) changes	
Conclusion on the stability of the methodology		The methodology is stable to factor(s) changes	
Conclusion on the suitability of the methodology based on the comparison coefficient		The accuracy of the methodology is confirmed	

3. Implementation Example and Discussion

Implementation Example

Thread inspection using the WAVELINE W800R profilometer can be implemented in various fields:

– In the production of aerospace components, threaded connections are used in critical structural elements such as engines, landing gear, and fuselage components. The use of a profilometer enables high-precision analysis of thread parameters, including pitch, flank angle, and mean diameter. For example, thread inspection of fasteners for turbine blades, where even minor deviations can lead to serious consequences due to high mechanical loads.

– In the manufacturing of automotive engines and transmissions, threaded connections ensure sealing and mechanical stability. Inspection of thread parameters using the presented method allows detection of deviations from nominal values and ensures compliance with ISO and DIN standards. This is especially relevant for threaded joints in turbocharger housings, where even microscopic defects can affect engine performance.

– In metrological control environments, the method can be applied for calibration of thread gauges to accurately assess their compliance with national standards.

– In nuclear and wind energy, thread joint control is critical for structural longevity. Using a profilometer

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allows the detection of micro-defects that may lead to mechanical degradation. For example, inspection of threaded studs in nuclear reactor systems operating under high temperature and pressure conditions.

Discussion

The WAVELINE W800R profilometer is a powerful tool for thread inspection; however, its application requires consideration of economic feasibility, physical limitations of the method, and potential improvements in the measurement process.

1) *Accuracy vs. Cost.* The use of the WAVELINE W800R profilometer is economically justified for high-precision measurements but may be excessive for mass production. However, using a cheaper alternative will not provide the same level of accuracy and detail.

2) *Method Limitations.* Contamination, wear, and surface defects can affect measurement accuracy. Using a standard profilometer is challenging for deep internal threads without special adapters or alternative measurement techniques.

3) *Result Reliability.* The WAVELINE W800R profilometer provides stable repeatability if the operator adheres to the measurement procedure. Stabilization of measurement conditions is essential, as external factors such as vibration and temperature may influence the results.

4) *Improvement Prospects*. Automation of analysis is possible, for example, through software that processes the point cloud data.

4. Conclusions

Based on the results of the conducted study and verification, the stability of thread inspection methods using the WAVELINE W800R profilometer was confirmed. The obtained experimental data indicate high accuracy, repeatability, and within-laboratory reproducibility of the method, which allows it to be used for the metrological control of thread gauges and threaded components in production.

Main advantages of the method:

– High measurement accuracy – the profilometer provides a detailed analysis of thread parameters, including flank angle, pitch, and mean diameter.

– Applicability across various industries – the method can be used in the aerospace, automotive, energy, and mechanical engineering industries, where thread inspection is critically important.

– Repeatability of results – under metrological laboratory conditions, the method demonstrates stable measurement performance under different operator influences.

– Applicability for gauge verification – the method enables the inspection of calibration samples for further use in production and metrological processes.

Limitations:

– Long measurement duration – due to the need for precise setup, scanning, and data analysis, the process takes a significant amount of time, which may be critical in mass production.

– Sensitivity to external factors – measurement accuracy depends on the stability of environmental conditions, requiring additional temperature and vibration control.

– Limitations in internal thread measurement – the method is effective for external threads but may require additional adapters or alternative techniques for inspecting internal threads.

Contributions of authors: formulation of research objectives and problem statements – **Kateryna Maiorova, Iryna Voronko;** review and analysis of information sources – **Viktor Kalinichenko, Vitalii Bocharov, Nabiyev Khayyam;** analysis of calibration and verification methodology – **Kateryna Maiorova;** conducting a series of measurements using the WAVELINE W800R profilometer – **Kateryna Maiorova, Viktor Kalinichenko, Vitalii Bocharov;** analysis of the obtained results – **Kateryna Maiorova, Iryna Voronko**; preparation of the draft manuscript – **Viktor Kalinichenko, Vitalii Bocharov, Nabiyev Khayyam;** writing of the final manuscript – **Kateryna Maiorova**; formulation of conclusions – **Kateryna Maiorova, Iryna Voronko.**

Conflict of Interest

The authors declare that there is no conflict of interest regarding the materials of this publication – financial, personal, authorship-related, or otherwise – that could have influenced the research and its results presented in this article.

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Data Availability

The manuscript has no associated data

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence methods while creating the presented work.

All authors have read and agreed to the published version of the manuscript.

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КОНТРОЛЬ НАРІЗІ ЗА ДОПОМОГОЮ ПРОФІЛОГРАФУ WAVELINE W800R: МЕТОДОЛОГІЯ ВЕРИФІКАЦІЇ МЕТОДИКИ

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І. О. Воронько, Набієв Хайям Сахіб огли

Предметом вивчення є методика контролю нарізі за допомогою профілографу WAVELINE W800R та її верифікація. Визначення параметрів точності методики калібрування та підтвердження її придатності до практичного використання. **Метою** роботи є дослідження та оцінка придатність методики калібрування різьбових калібрів із застосуванням профілографу WAVELINE W800R на основі аналізу прецизійності, відтворюваності та правильності вимірювань. **Завдання** дослідження включають: розробку та застосування алгоритму оцінювання методики калібрування; визначення основних метрологічних характеристик, що впливають на точність вимірювань; оцінювання збіжності та внутрішньолабораторної відтворюваності методики; аналіз стійкості методики до впливу різних факторів; визначення правильності вимірювань за коефіцієнтом порівняння. **Використовувані методи** включають експериментальні дослідження точності методики калібрування із застосуванням статистичних критеріїв (Кохрена, Граббса, Фішера, Стьюдента) для перевірки однорідності дисперсій та виключення аномальних значень. Було здійснено багатократні повторні вимірювання параметрів різьби, аналіз впливу зовнішніх факторів та порівняння результатів за критерієм k. **Отримані результати** підтвердили можливість застосування профілографу WAVELINE W800R для високоточного вимірювання різьбових калібрів. Було встановлено, що методика демонструє достатню збіжність та внутрішньолабораторну відтворюваність. Проведений аналіз стійкості методики до змін умов довкілля засвідчив її стабільність. Методика пройшла перевірку правильності вимірювань за коефіцієнтом порівняння та відповідає вимогам метрологічного контролю. **Висновки:** Методика контролю нарізі за допомогою профілографу WAVELINE W800R підтвердила свою придатність для використання в лабораторних умовах. Вона може бути впроваджена в метрологічну практику для контролю різьбових калібрів. Разом із тим встановлено, що проведення верифікації вимагає значного часу, що слід враховувати при організації калібрування. Рекомендовано проводити повторну верифікацію методики після калібрування еталонного обладнання.

Ключові слова: верифікація методики калібрування; профілограф WAVELINE W800R; прецизійність вимірювань; збіжність та відтворюваність; контроль нарізі.

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