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THE IMPORTANCE OF MEASUREMENT UNCERTAINTY DURING THE GAUGE BLOCK CALIBRATION IN DETERMINING COMPLIANCE WITH SPECIFICATIONS

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Abstract

This article deals with the selected problems related to the calibration of gauge blocks. It describes basic terms and definitions concerning principles of determining the conformity of calibration results with specifications, such as measurement uncertainty and measurement traceability. The requirements for laboratories accredited according to ISO/IEC 17025:2017 were discussed that are related to the declaration of compliance with the specification. Guidelines are given on decision rules and compliance principles based on ILAC-G8:09/2019 and JCGM 106:2012 in terms of the guard bands used and the associated risks of making an erroneous decision and the application of two decision rules: binary and nonbinary. The presented problems were supported by an analysis regarding calibration of the gauge blocks by the interferometric and comparative method with regard to measurement uncertainty and deviations of the length in relation to the nominal length for individual grades in accordance with ISO 3650:1998. As the theoretical analysis has shown, there are no sources in the literature that would allow one to assess the risk of making the wrong decision during the calibration of gauge blocks. Therefore, the authors believe that the results presented in this paper will be of interest both to researchers dealing with the problem of estimating measurement uncertainty and to the staff of measurement laboratories.

Keywords: calibration, uncertainty, gauge blocks, Monte Carlo method.

1. Introduction

Transferring units of measurement is one of the basic tasks of metrology. According to the current definition, the base unit of length, which is one meter, is implemented as a superior standard using interferometers. To reproduce the length units in a practical way, standards of lower level, such as gauge blocks, are used (see Fig. 1). For this reason, gauge blocks are an extremely important tool for maintaining traceability in the area of length measurements.

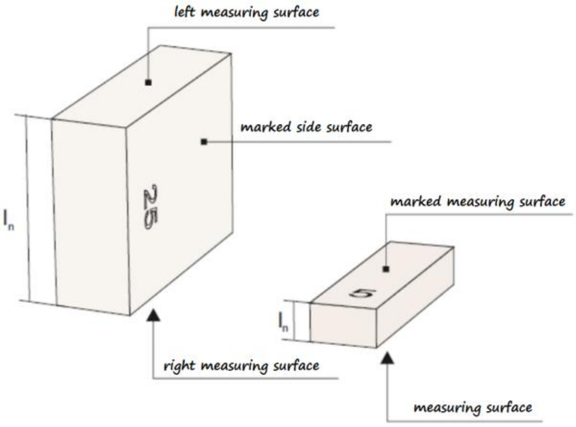

Fig. 1. Gauge blocks and their surfaces

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Gauge blocks are cuboidal length standards defined in ISO 3650:1998 [1]. They are usually made of steel, ceramics, or carbides. Reproduction of length units with gauge blocks is possible because they have a pair of mutually parallel measuring surfaces. The length of a gauge is defined as the distance between these surfaces from each other.

This distance is determined on the basis of the so-called central points lying at the intersection of the diagonals of the measuring surfaces of the gauge block. This distance is defined as the so-called "central length" (see Fig. 2).

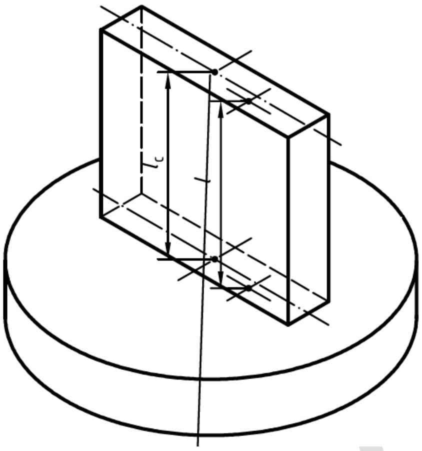

Fig. 2. The central length of the gauge block - l_c [1]

An important factor in assuring the traceability and in obtaining reliable measurement results is the calibration of standards and measuring instruments. In general, the process of the calibration allows establishing relations between quantity values and corresponding indications of the measuring system. The exact definition of traceability is given in [2]. Without the calibration maintaining measurement traceability would not be possible. It is fundamental to keep appropriate time intervals between calibrations. They can be set rigidly and depending on possible needs. Guidelines for this purpose can be found in [3].

ISO 3650:1998 [1] describes two methods for calibrating gauge blocks: the direct method, using a laser interferometer, and the comparative method.

The principle of measurement with the use of an interferometer is based on the observation of changes in interference fringes resulting from the superimposition of the measurement and reference beams. In the case of measuring the length of gauge blocks, the gauge beam is reflected from a stationary mirror, while the measuring beam is reflected from the mirror attached to the end of the gauge block being measured [4, 5]. The interference method is recommended for grade K gauge blocks. In turn, grade K gauge blocks are used to calibrate gauge blocks of lower grades through the comparison process. The calibration of the gauge blocks through the comparison is cheaper and less time-consuming than the interferometric calibration. However, the interferometric calibration due to its accuracy and precision is the superior method for calibrating gauge blocks.

In the mechanical comparative method, the unit of length measurement is transferred directly from the reference gauge blocks to the gauge blocks to be calibrated. The difference between the central lengths of the reference gauge block and the gauge block under calibration is determined using a two-sensor comparator [6].

The typical two-sensor comparator consists of the measurement base, the measuring table with the gauge block positioning device, and two high-accuracy length indicators connected to an electronic measuring instrument with numerical display. The central length or the deviation of the central length from the nominal length of the gauge block are the basic parameters determined during the comparative calibration. The comparative method of gauge blocks calibration is widely used in calibration laboratories, and the issue of determining the central length of gauge blocks and the uncertainty of these measurements are often discussed in the literature.

In general, the available research works on the calibration of gauge blocks can be divided into two groups: the former referring to direct calibration (using interferometers) and the latter referring to the calibration using the comparative mechanical method.

In the case of the interferometric method, an interesting concept has been described in [8, 9]. The authors of these works developed a gauge block calibration system, which, apart from the typical Michelson interferometer, applies an optical system based on a central interference fringe of polychromatic light. The problem of calibrating gauge blocks with the use of optical systems has also been investigated in [10].

In the case of the interferometric calibration, monitoring of the influence of environmental conditions on the change in the properties of the laser beam used for the calibration process is fundamental. This is particularly important when measuring long gauge blocks. Ranusawud *et al.* in [11] studied the impact of environmental conditions on the refractive index of the the air in measurements of length of long gauge blocks. In the analysed case, the authors managed to develop correction factors that allowed a significant reduction of measurement uncertainty.

In [12], the authors propose the use of an iodine-stabilized diode laser system as a light source. The results presented by the authors show that proposed system permits obtaining similar results as for typical laser heads used so far, while reducing the cost and size of the optical system.

In the case of interferometric measurements of gauge blocks, the paper [13] is worth noting. Authors of this work propose contactless system for automatic calibration of gauge blocks. The system is based on the combination of laser and low-coherence interferometry.

In the field of the mechanical comparative method, the Slovenian group of researchers has published a series of papers concerning the problem of uncertainty evaluation [14-16]. In [14], the uncertainty budget was developed taking into account specific factors such as the inaccuracy of determining the points based on which the location of the central point was calculated and the value of the measurement force on the measurement results. In [15], the cases of calibration of gauge blocks made of different materials were analysed. In turn, the paper [16] presents the methodology for determining uncertainty and its results for national length standards in Slovenia. The proposed methodology allowed a significant reduction in the value of measurement uncertainty using the mechanical comparative method.

A relatively simple method that was proposed to reduce the uncertainty of the comparative method is described in [17]. The method is based on the use of the average of two reference values for one difference in length values. Using the average of two reference values permits reducing the components of the uncertainty associated with the determination of the length of the reference blocks.

It should also be noted that in the literature there are available works focused not only on the calibration of length standards, but also on the calibration of angular gauge blocks [18].

None of the papers presented above described *Monte Carlo* (MC) uncertainty evaluation or the problem of assessing conformity to specification using guard bands. In general, taking into account the literature studies carried out, it is noticeable that there are no sources in the literature on the risk assessment of making the wrong decision during the calibration of gauge blocks. For this reason, the authors of this article attempted to analyse these issues for both the interferometric method and the mechanical comparative method. The second chapter presents the basic concepts related to the problem of estimating uncertainty and determining the criteria for making decisions about compliance with the specification. The third chapter presents the results of experimental research. Chapter four presents a discussion of the results obtained, while chapter 5 contains conclusions and potential directions for further research.

2. Theoretical background

2.1. Expression of measurement uncertainty

A measurement result is generally expressed as a single measurand value attributed by a measurement uncertainty. There are a few definitions of measurement uncertainty. One of them refers to the interpretation of uncertainty as a range of variability of the mesurand determined with the assumed probability [2]. The importance of the issues related to measurement uncertainty is evidenced by the number of documents of the most important metrological institutions related to this subject [19-21].

The principles of measurement uncertainty assessment are presented in [7, 19]. Propagation of distributions using a Monte Carlo method and additional requirements for calibration laboratories operating on the basis of the standard ISO/IEC 17025:2017 are given in [20].

GUM (*Guide to the Expression of Uncertainty in Measurement*) distinguishes between two types of uncertainty evaluation:

- Type A (by statistical analysis).
- Type B: (by means other than statistical analysis).

The GUM concept of measurement uncertainty assessment can be presented as follows:

1. Define the relation between the output quantity and all the input quantities.
2. Estimate the values of the input quantities.
3. Estimate the standard uncertainties of the input quantities, through statistical analysis or by other means.
4. Determine the sensitivity coefficient that belongs to each input quantity.
5. Calculate the combined uncertainty of the output quantity.
6. Determine a coverage factor that corresponds to the chosen coverage probability.
7. Calculate the expanded uncertainty of the output quantity.
8. Report the measurement result together with the expanded measurement uncertainty.

The basic idea of the MC method [19] is the principle of probability distribution propagation. It is implemented through the developed mathematical model of measurement with the use of Monte Carlo simulations. The result is the probability distribution associated with the output quantity, which is determined on the basis of the distributions of input quantities. The measurement result is presented in the form of parameters of this distribution: expected value, standard deviation and quantile distribution for a specific probability.

The expected value is regarded as the best estimate of the measurand, and the standard deviation as the standard uncertainty associated with this estimate. This method can be used when the conditions for the GUM approach are not met, for example, due to the complexity of the measurement model.

The mathematical model for measuring the scalar input quantity can be expressed by the following relationship:

$$Y = f(X) \tag{1}$$

where:
Y – output quantity
X – input quantity represented by the set of N input quantities $(X_1, \ldots, X_N)^T$

Each of the input quantities X_i is a random variable with possible values ξ and expected value x_i. The output value Y is a random variable with possible values η and expected value y.

Figure 3 shows the idea of uncertainty evaluation according to GUM based on the concept of uncertainty propagation (acronym GUF) and using MC simulation based on the principle of propagation of distributions (acronym MCM).

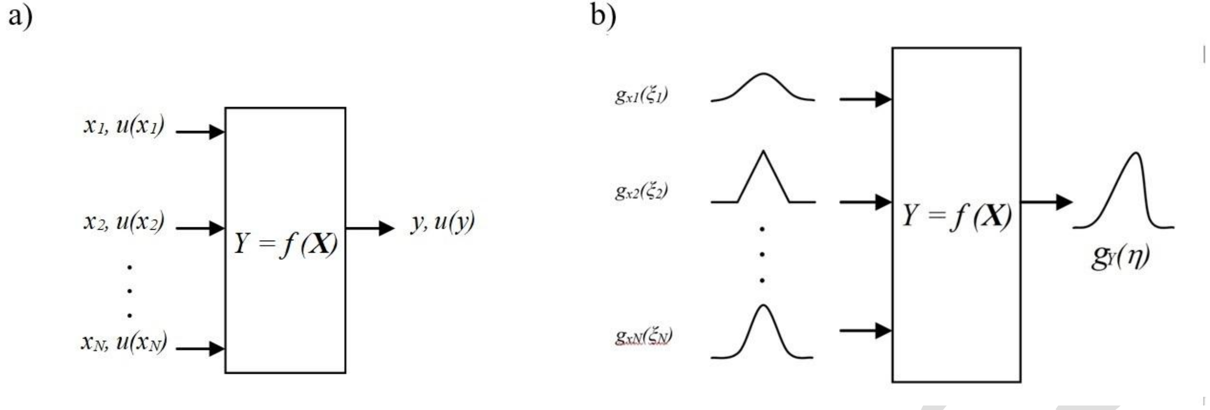

Fig. 3. Difference between the principle of uncertainty evaluation according to:
a) GUM uncertainty framework (GUF) b) Monte Carlo Method (MCM)

Symbols x_i, where i=1, 2, … , N shown in Fig. 3a are the input quantities, each of which is assigned an uncertainty denoted by $u(x_i)$. The output quantity in this figure is denoted by y, and its uncertainty $u(y)$ is calculated taking into account the uncertainties of the input quantities.

As mentioned above, in the Monte Carlo method, instead of numerical values, the input quantities are probability density functions of the quantities x_i, where i=1, 2, … , N, which are marked accordingly in Fig. 3b by $g_{xi}(\xi_i)$. Based on these results, the probability density function of the output quantity Y *is* determined, denoted in the figure by $g_Y(\eta)$.

2.2. Decision rules and statements of conformity

The results obtained during calibration are the basis for determining the conformity of the standards and measuring instruments with the specification. In calibration laboratories accredited according to ISO/IEC 17025:2017, compliance with the specification is mandatory if the customer requires so. The specification or requirement and the decision-making principle should be clearly defined and communicated to and agreed with the customer. According to [22], the decision rules describe how measurement uncertainty contributes to the determination of the compliance with specified requirements.

Detailed guidance on decision rules and statements of conformity are included In JCGM 106:2012, ILAC-G8:09/2019 and ISO 14253-1:2017-1 [22-24]. These documents define, among others, such terms as:

1. *Tolerance Limit* (*TL*) (Specification Limit) - specified upper or lower bound of permissible values of a property.
2. *Tolerance Interval* (*TI*) - interval of permissible values of a property.
3. Acceptance Interval - interval of permissible measurand values.
4. Rejection Interval - interval of non-permissible measurand values.
5. Guard Band (w) - interval between a tolerance limit and a corresponding acceptance limit where length $w = |TL-AL|$.
6. *Maximum Permissible Error* (*MPE*) (of Indication) - for a measuring instrument, extreme value of measurement error, with respect to known reference quantity value, permitted by specifications or regulations for a given measuring instrument.
7. *Test Uncertainty Ratio* (*TUR*) - the ratio of the tolerance interval of a measurement quantity, divided by the 95 % expanded measurement uncertainty of the measurement process where $TUR = TI/U$.

Figure 4 graphically shows the relationship between the tolerance interval (specification interval), the acceptance interval and the guard band (*w*).

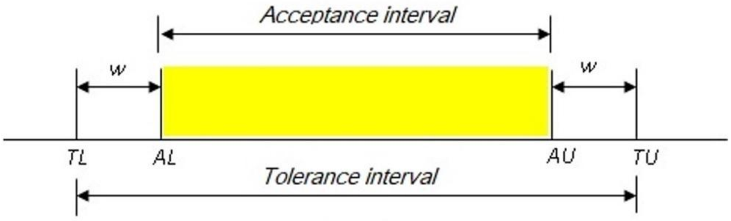

Fig. 4. Guard bands for two sided acceptance interval having lower and upper tolerance limits

ILAC-G8:09/2019 provides two decision rules: binary and non-binary. In the case of the binary rule, the decision is limited to two choices: pass or fail. A non-binary decision rule exists when multiple terms may express the result (pass, conditional pass, conditional fail, fail) [25].

A guard band that has a length equal to zero, $w = 0$, infers that acceptance is when a measurement result is below a tolerance limit. This is called simple acceptance [26, 27]. For this principle, the probability to be outside the tolerance limit may be as high as 50 % in the case when a measurement result lies exactly on the tolerance limit (assuming a symmetric normal distribution of the measurements results).

Often, the guard band is based on a multiple r of the expanded measurement uncertainty U where $w = r \times U$. In the case of a binary decision rule, a measured value below the upper limit of acceptance AU and above the lower limit of acceptance AL is accepted.

Although it is common to use a guard band $w = U$, there may be cases where a multiplier other than 1 is more appropriate. Table 1 provides examples of different guard bands to achieve certain levels of specific risk, based on the application of the customer.

Table 1. Examples of different guard bands to achieve certain levels of specific risk [23].

Guard band ***W***	**Specific Risk** **(Probability of False Acceptance)**
$3U$	< 1 ppm
$1.5U$	< 0.16 %
U	< 2.5 %
$0.83U$	< 5 %
0	< 50 %

3. Results

The issue of determining compliance with the specification will be presented in this Section on the example of the calibration of gauge blocks by the interferometric and the comparative method.

Expanded uncertainty of the measurement of the deviation of the central length from the nominal length of the gauge block based on the method of calibrating gauge blocks on an interferometer with lasers with a wavelength of 633 nm and 543 nm, carried out in the National Metrology Institute of Poland (Central Office of Measures) is defined by the formula

$$U = \sqrt{21^2 + 0.2^2 \cdot l_n^2} \tag{2}$$

where :

U – expanded uncertainty determined in the Central Office of Measures (using interferometric method), nm

l_n – nominal length of the gauge block, mm.

Figure 5 shows the achievable *TUR* values for the interferometric calibration method for grade K gauge blocks in the range from 0.5 mm to 100 mm. The smallest values of *TUR* = 9.5:1 occur for gauge blocks with a nominal length in the range from 0.5 mm to 10 mm, while the largest value of *TUR* = 22.7:1 for a gauge block with a nominal length of 80 mm.

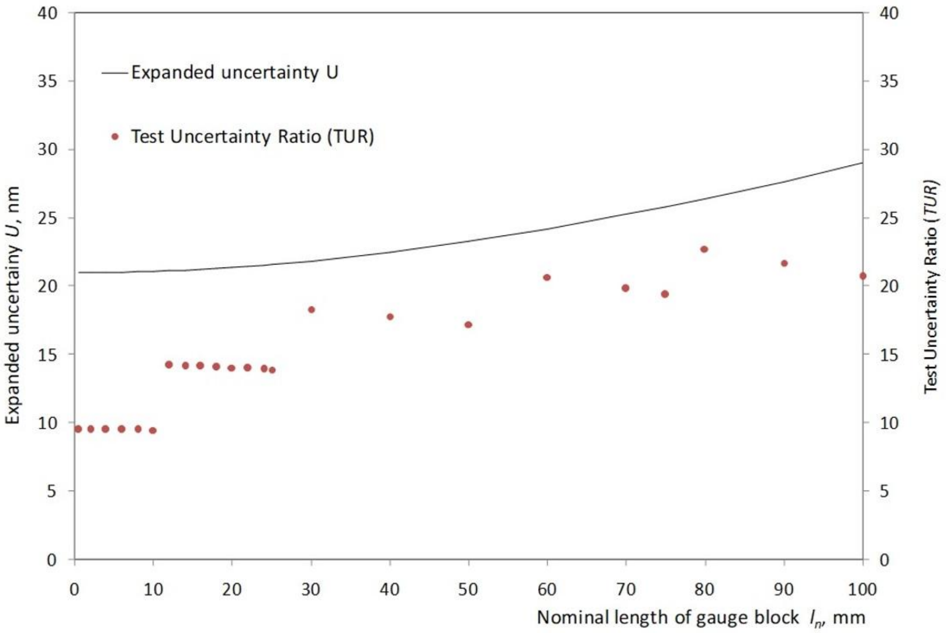

Fig. 5. Test Uncertainty Ratio (*TUR*) for interferometric calibration method of gauge blocks

The calibration of the gauge block by the mechanical comparison method is carried out by comparison using a comparator and the reference standard (gauge block) of the same nominal length and the same material as the gauge block that is under calibration [28].

The length of an unknown gauge block at the reference temperature is obtained from the relationship [19]:

$$l_X = l_S + \delta l_D + \delta l + \delta l_C - l_n \cdot \;\; \alpha \cdot \delta_t + \delta_\alpha \cdot \Delta t \;\; - \delta l_V \tag{3}$$

where:
l_X – the length of the unknown gauge block at the reference temperature,
l_s – the length of the reference gauge block at the reference temperature t_0 = 20 °C according to its calibration certificate,
δl_D – change in the length of the reference gauge block since its last calibration due to drift,
δl – observed difference in length between the unknown and the reference gauge block,
δl_C – correction for nonlinearity and offset of the comparator,
l_n – nominal length of the gauge blocks considered,
$\alpha=(\alpha_X-\alpha_S)/2$ – average of the thermal expansion coefficients of the unknown and reference gauge blocks,
$\delta_t=t_X-t_S$ – temperature difference between the unknown and reference gauge blocks,
$\delta_\alpha=\alpha_X-\alpha_S$ – difference in the thermal expansion coefficients between the unknown and reference gauge blocks,
$\Delta t=(t_X-t_S)/2-t_0$ – deviation of the average temperature of the unknown and the reference gauge blocks from the reference temperature,
δl_v – correction for noncentral contact of the measuring faces of the unknown gauge block.

An example of the calibration uncertainty budget of a gauge block with a nominal length of 10 mm using a mechanical comparator is shown in Table 2.

Table 2. An example of calibration uncertainty budget

Quantity X_i	**Estimate** x_i	**Standard uncertainty** $u(x_i)$	**Probability distribution**	**Sensitivity coefficient** c_i	**Uncertainty contribution** $u_i(y)$
l_S	10.000 0020 mm	10.55 nm	Normal	1.0	10.55 nm
δl_D	0 mm	11.56 nm	Triangular	1.0	11.56 nm
δl	0.000 080 mm	8.66 nm	Normal	1.0	8.66 nm
δl_C	0 mm	20.73 nm	Rectangular	1.0	20.73 nm
δt	0 ºC	0.0347 ºC	Rectangular	$-115\ \text{nm}\ ^\circ\text{C}^{-1}$	-3.98 nm
$\delta\alpha \cdot \Delta t$	0	$0.236 \cdot 10^{-6}$	-	-10 mm	-2.36 nm
δl_V	0 mm	4.88 nm	Triangular	-1.0	-4.88 nm
l_X	10.000 100 mm	**Combined standard uncertainty $u_c(y)$:**			28.2 nm

It should be noted that the drift problem is described in the ISO 3650 standard [1], and in particular in Section 6.2.4 of this standard. According to the standard guidelines, if the last calibration of the gauge block was carried out recently, zero can be taken as the value of the change in the length of the reference gauge block. Then the uncertainty contribution will be determined based on the standard uncertainty, as shown in Table 2.

The temperature measurements, on the basis of which some of the presented calculations were carried out, were made with the LB520 thermometer. The values of relevant thermal coefficients were taken from the specification provided by the manufacturer of the gauge blocks.

The expanded uncertainty for the coverage factor $k = 2$ is:

$$U = 28.2 \cdot 2 = 56.4\ \text{nm} \approx 56\ \text{nm} \tag{4}$$

The measured value of the nominal 10 mm gauge block is 10.000 100 mm ± 56 nm. The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor k such that the coverage probability corresponds to approximately 95 %.

The Geometric Quantity Measurement Laboratory of Kielce University of Technology accredited by Polish Centre for Accreditation (AP 188), performs calibration of gauge blocks with nominal lengths in the range from 0.5 mm to 100 mm by the comparative method with the use of grade K reference gauge blocks.

The expanded uncertainty of determining the deviation of the central length of gauge blocks from the nominal length based on the comparative method carried out in the Geometric Quantity Measurement Laboratory of Kielce University of Technology (AP 188) is given by the formula:

$$U = \sqrt{55^2 + 1.01^2 \cdot {l_n}^2} \tag{5}$$

where :
U – expanded uncertainty for the coverage factor $k = 2$, nm
l_n – nominal length of gauge block, mm

This relationship was determined based on the uncertainty budget prepared in accordance with the recommendations contained in the document EA-4/02 M:2022 Evaluation of the uncertainty of measurement in calibration.

In Fig. 6. the achievable *TUR* values for this calibration method for individual grades of gauge blocks in the range from 0.5 mm to 100 mm are presented. The smallest *TUR* = 2.1:1 ÷3.1:1 values occur for grade 0 gauge blocks, while the highest *TUR* = 8.0:1 ÷ 12.2:1 values for grade 2 gauge blocks.

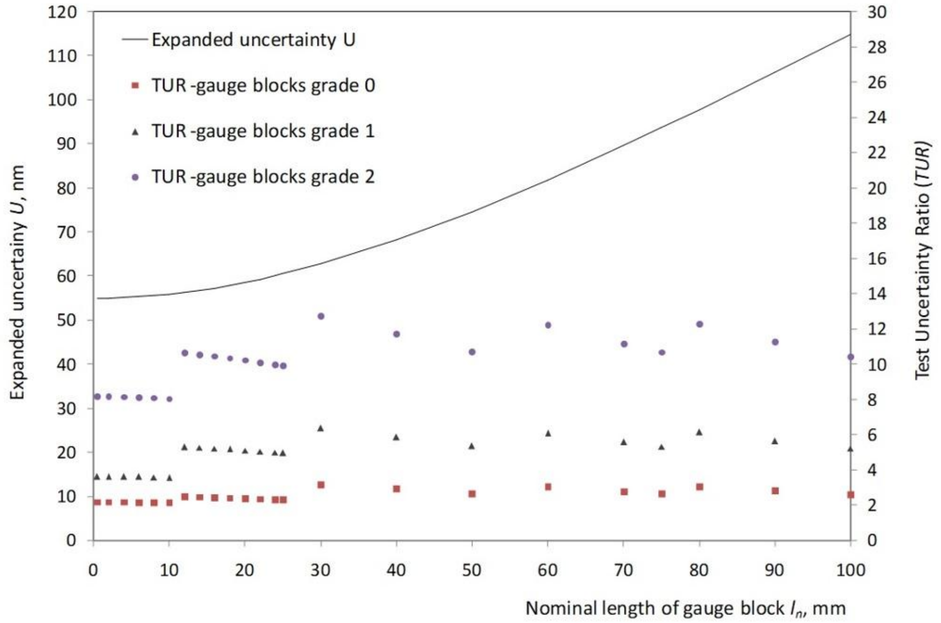

Fig. 6. Test Uncertainty Ratio (*TUR*) for mechanical comparative calibration method of gauge blocks

4. Guard bands and the assessment of the risk

In order to assess obtained results, firstly the analysis of the width of the acceptance interval has been performed.

The analysis of the width of the acceptance interval assuming a guard band with a width of $w = U$ is presented in Fig. 7. The diagram in Fig. 7 shows the results for both calibration methods and for gauge blocks grade and nominal lengths, which have a minimum achievable value of the *TUR* coefficient. In the case of calibration by the interference method for grade K gauge blocks in the nominal length range l_n from 0.5 mm to 10 mm, the acceptance interval is 89.5 % of the limit deviation. In the case of the comparative method, for a grade 0 reference plate with a nominal length of l_n = 10 mm, the acceptance interval is only 53.3 % of the limit deviation.

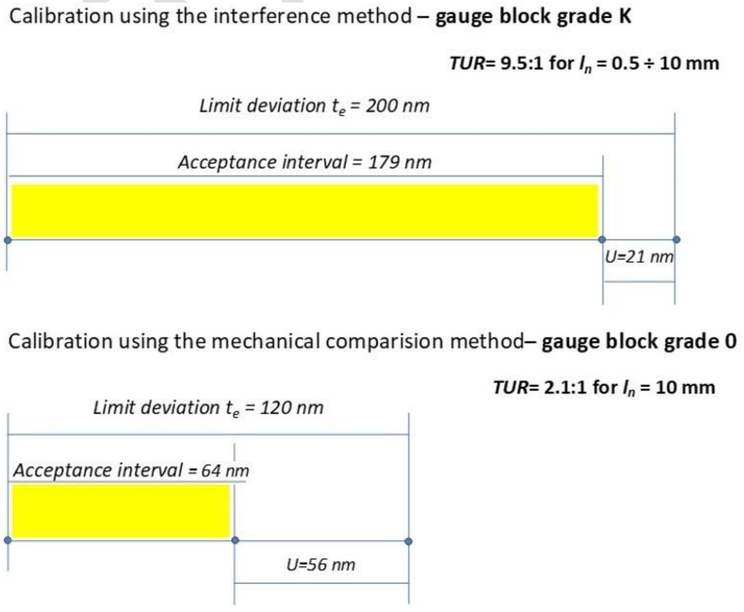

Fig. 7. Guard bands with a width of $w = U$ for calibration by interference and mechanical comparative methods for gauge blocks with the smallest *TUR* values

In order to validate the prepared uncertainty budget for the calibration of the reference gauge block using the comparative method, the uncertainty was evaluated using the Monte Carlo method.

The evaluation of the calibration uncertainty of the gauge block with the nominal length l_n = 10 mm was carried out by the Monte Carlo method for identical input data and probability distributions as in the case of the presented uncertainty budget based on GUF. MC simulation was performed for M = 100 000 trials.

As a result of the calculations carried out, the expanded uncertainty U = 56 nm was obtained. The difference in the expanded uncertainty values using both methods is 0.7 %.

Figures 8 and 9 show the results obtained along with an assessment of the risk of making the wrong decision for the case of calibration of grade 0 and grade 1 gauge blocks. The values of the probability distribution function marked in red indicate the risk area of making a wrong decision.

The assessment of the risk of making a wrong decision when determining the calibration compliance with the specification of a gauge block whose nominal length is l_n = 10 mm and the central length is l_x =10.000 100 mm by the comparative method using both methods of uncertainty estimation has been given in Table 3.

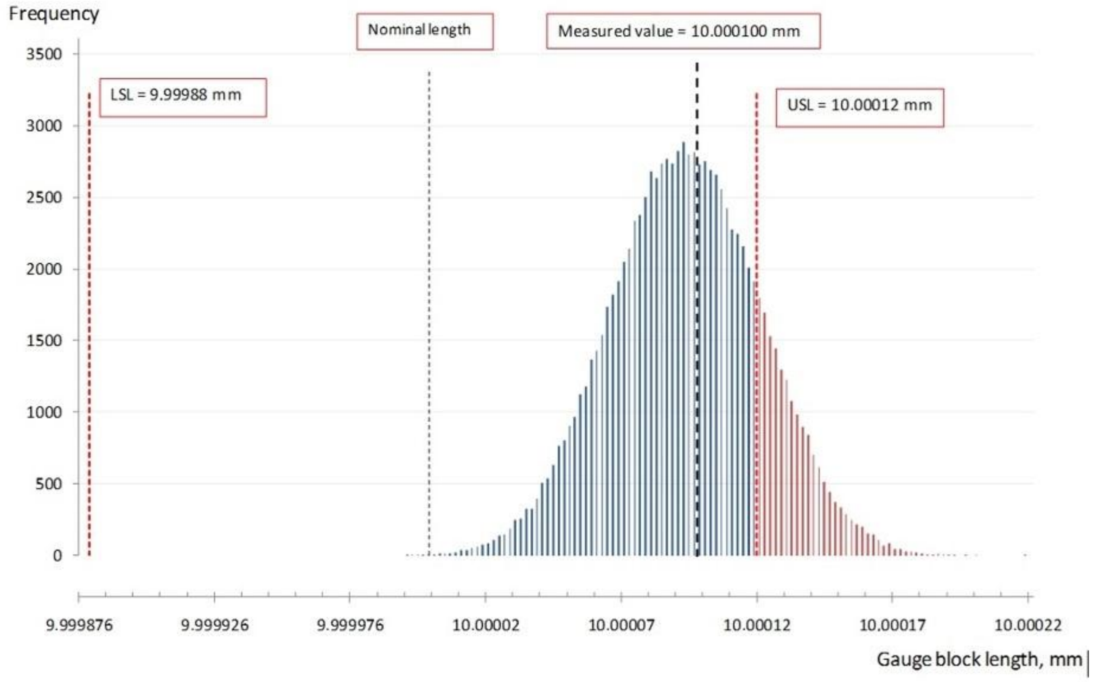

Fig. 8. Assessment of the risk of making a wrong decision using the Monte Carlo uncertainty evaluation (grade 0 gauge blocks)

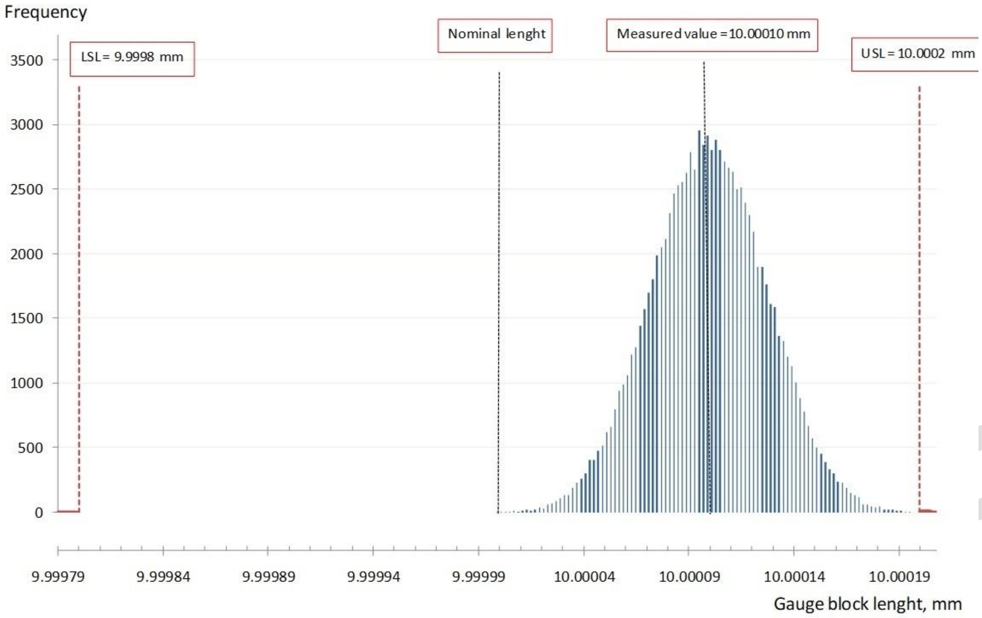

Fig. 9. Assessment of the risk of making a wrong decision using the Monte Carlo uncertainty evaluation (grade 1 gauge blocks)

Table 3. Assessment of the risk of making a wrong decision

Class gauge block	Risk of making a wrong decision, %	
	Method for the evaluation of measurement uncertainty	
	GUF	MCM
0	23.9	23.1
1	0	0
2	0	0

Fig. 10 presents the values of the risk of making an incorrect conformity assessment decision for a grade 0 gauge block with a nominal length of l_n = 10 mm, for which the permissible limit deviation of the central length is t_e = 120 nm in the case of the expanded uncertainty of calibration using a comparator U = 56 nm, as a function of the deviation of the central length from the nominal length.

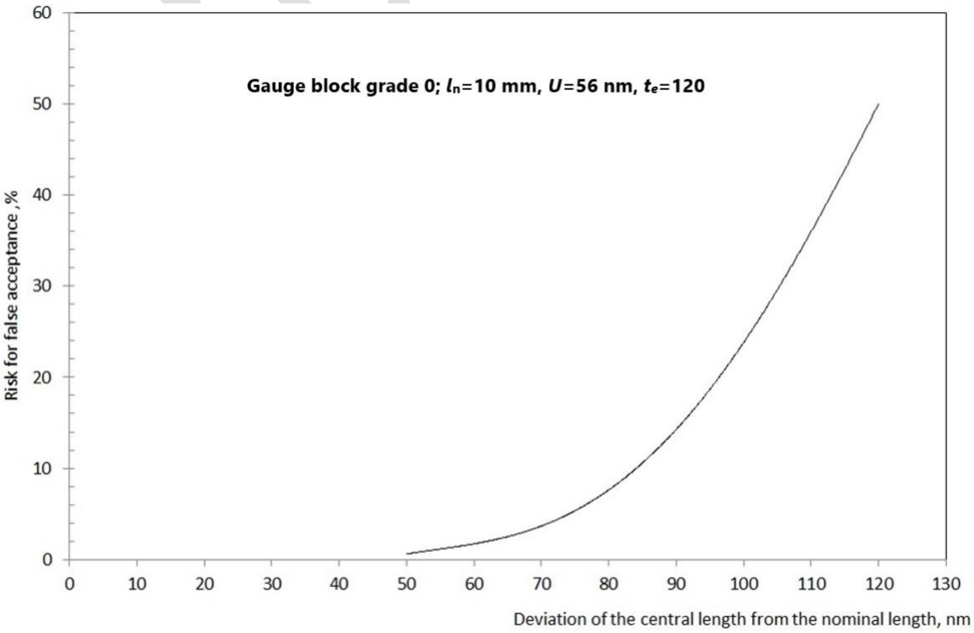

Fig. 10. Values of the risk of making an incorrect conformity assessment decision for a grade 0 gauge block with a nominal length of l_n = 10 mm

5. Conclusions

The above analysis was carried out in terms of obtainable values of the TUR (Test Uncertainty Ratio) defined as the value of the tolerance limit TL of the measurand and 95 % of the extended uncertainty of measurement U, where $TUR = TI/U$ based on the declared uncertainty values extended by the Central Office of Measures for the interference method and the Geometric Quantity Measurement Laboratory of the Kielce University of Technology (AP 188) for the comparative method. It should be emphasized that the CMC (Calibration and Measurement Capability) declared by the laboratory is comparable to the CMC values declared by other accredited calibration laboratories. The relative widths of the acceptance intervals were compared assuming a guard band of a width $w = U$, for both calibration methods in relation to the identified least favourable cases.

As a result of the analysis, it should be stated that in the case of calibration of grade K gauge blocks using the interference method, the TUR values are very good even for the least favourable cases and amount to TUR = 9.5: 1.

The situation is very different in the case of calibration of grade 0 gauge blocks using the comparative method, for which the requirements for deviations of the limit of the central length in relation to the nominal length are the most restrictive. In this case, the obtained TUR values for the least favourable cases are below TUR = 3:1, which is associated with an increased risk of making an erroneous decision (higher probability of erroneous acceptance) when using a protective band with a width equal to zero, *i.e.* applying the principle of simple acceptance.

To sum up the conducted research, it should be stated that the theoretical analysis and experimental tests permitted the determination of values that facilitate the assessment of the risk of making an wrong decision during the calibration of the gauge blocks. As the literature on this subject is relatively poor, the authors assume that this work may be useful not only for researchers, but also for the staff of measurement laboratories performing calibrations.

In the near future, the authors plan to conduct additional research, which will involve the application of the developed procedures for a larger number of data.

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