A novel method for a stylus profilometer gauge calibration with a use of gage blocks and sine bar

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Abstract-Stylus profilometer gauge calibration, which often involves complicated procedures and demands expensive calibration standards, is substantial for ensuring both repeatability and reliability of surface roughness measurement results. However, in spite of numerous calibration methods being proposed, not only has the problem remained unsolved, but it even arose as incredibly wide range stylus profilometers came into the market recently. In the paper, a novel method is proposed in order to simplify the calibration process and interpretation of its results without decline in accuracy. The main idea is to replace the costly standards dedicated to profilometers with a sine bar and gage blocks, which are a must-be in every metrology laboratory. As a result, a calibration of these high-accuracy measuring instruments becomes fast and inexpensive. Moreover, this time and cost efficiency corresponds with the intuitiveness and easiness of interpreting calibration outcomes. In the paper, the core principles of the method are outlined and some experimental results demonstrating its performance are presented.

I. Introduction

High accuracy surface texture measurement is a rapidly developing field of metrology. Its applications are no longer limited to evaluation of the compliance with the specification of industrial objects, but they expanded to the fields such as medicine and cosmetology (especially researches on the aging process and effectiveness of rhytides treatment) [1]. As a result, the dozens of surface roughness measurement techniques were introduced. Despite this, the stylus method, which originated in the beginning of the previous century, is still the most popular one due to its reputation as the reliable and reproducible.

The groundwork of this consistency and dependability is a proper profilometer gauge calibration. Numerous methods based on a use of the spacing (type C) or depth (type A) measurement standards were developed [2]. However, these standards enable user to calibrate the instrument only at few isolated points of the machine measuring range. The solution developed by the manufacturers of the measuring equipment recently is a use of the precision hemisphere (type E1) [2] or prism standard (type E2) [2]. It is not free from drawbacks, too. Not only does it demand advanced signal processing and comprehensive knowledge in order to aptly interpret the calibration results but, above all, using an artefact dedicated only to the one, specific, type of instrument. The reason is that it has to be ensured that the spherical, not any other, part of a stylus tip remains in contact with the surface of a standard during the measurement [3]. In effect, even a minor modification of the same machine, such as replacing the stylus with a one having another tilt length, may lead to a necessity for using another calibration standard. It makes this method difficult to be adopted in industrial applications, especially when the extremely high cost of artefact manufacturing is considered.

However, to meet a demand for a reliable and, what is the most important, economical stylus profilometer gauge calibration procedure, a novel method of performing so has been developed in the Institute of Metrology and Biomedical Engineering in Warsaw University of Technology. The main idea is to replace the costly standards mentioned above with a sine bar and gage blocks, which are a must-be in every metrology laboratory. In the paper, the core principles of the method are outlined. Also, a performance of the procedure has been investigated. To verify the concept applicability a set of experiments was conducted with the Form Talysurf PGI 830 by Taylor Hobson. This instrument is characterised by an uncommonly wide gauge range of 8 mm. The results obtained with the machine and the calibration uncertainty evaluation are presented and discussed in the following sections, too.

II. Principle

The profilometer gauge calibration procedure with a use of the gage blocks and a sine bar consists of two main steps shown in Fig. 1. Firstly, a sine bar (3) with a gage block (1) on it is placed on a levelled measurement table (4) of a profilometer and the profile of one of the gage wringing surfaces is measured. Then, one of the sine bar rollers is raised by a known distance using another gage block (5) and the same profile of the gage block (1) should be measured again.

1 – Gage block
2 – Profilometer gauge
3 – Sine bar
4 – Measurement table
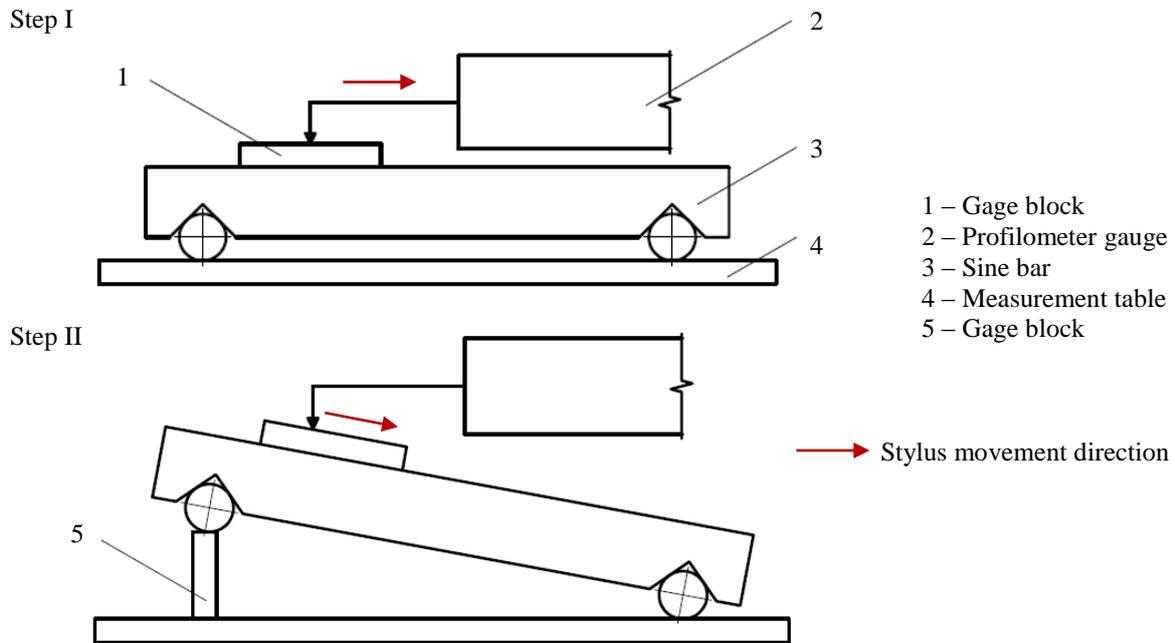5 – Gage block

Stylus movement direction

Figure 1. The calibration procedure

When both data sets are registered, straight lines are fitted to them using the least squares criterion and an angle between them α is calculated. Also, the nominal value of this angle α_n can be counted by the application of the sine rule, as both the distance between the two sine bar rollers and the amount the bar is tilted is known. Then, the tangents of these angles are determined and compared. As a result, a calibration coefficient Z is given:

$$Z = \frac{\tan \alpha}{\tan \alpha_n} \qquad (1)$$

Any corrections of gauge sensitivity are not needed, if Z is equal to 1.000 and gauge linearity is assured. Otherwise, the gauge indications should be divided by the Z value.

It needs to be mentioned that the measuring range of a instrument gauge being calibrated determines the choice of a sine bar and a nominal dimension of gage block (5). The dimensions of the measuring setup used in the research are presented in Table 1.

Table 1. Calibration setup parameters

Calibration range	R	6.4 mm
Gage block (1) nominal length	N_1	2.5 mm
Gage block (5) nominal length	N_5	25.0 mm
Evaluation length	P	25.6 mm
Sine bar length	L	100.0 mm
Nominal angle	α_n	14.478 °

The PGI 830 gauge has been calibrated in a range of 6.4 mm (80% of a nominal measuring range) due to the recommendations of the instrument manufacturer [4] as in the sections close to the lower and upper measuring range limit gauge response curve becomes non-linear (Fig. 2). In effect, the gauge work in these parts of range should be avoided.

Other calibration methods, such as the one which demands a use of the precision hemisphere standard, provide a user only with a general information concerning performance of the measuring gauge. Despite the calibration coefficient is estimated, it is impossible to assess if there are any linearity deviations of instrument gauge characteristics as the standard form deviations impact cannot be excluded from the registered data. On the contrary to applying the hemisphere standard calibration procedure, a use of the proposed method enables user to separate these two signals easily: simply by excluding the first, levelled, profile - referring to the artefact form deviations, from the tilted one as it is shown in Fig. 3.
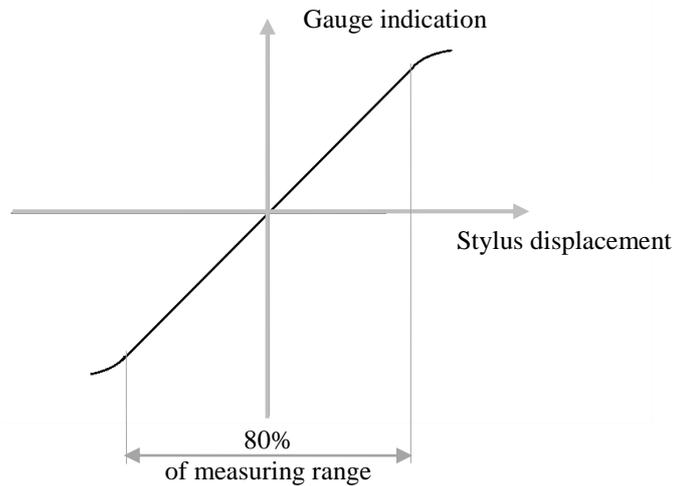

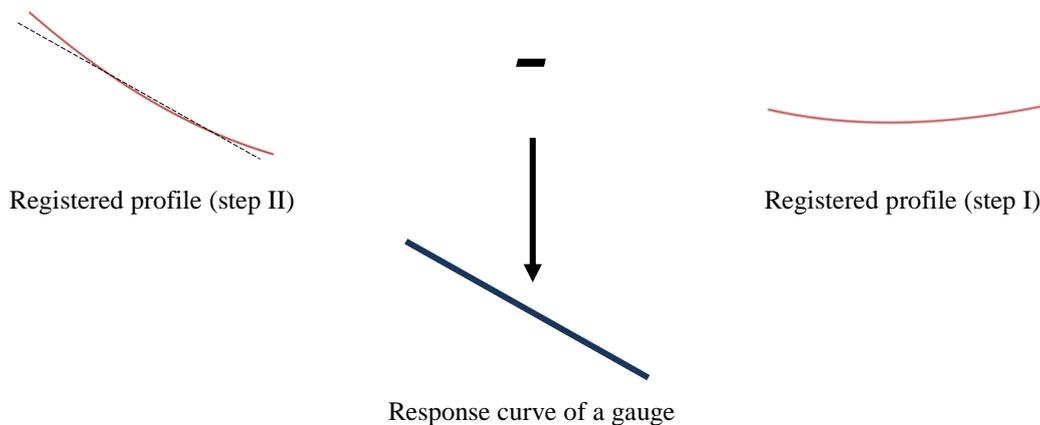Figure 2. The response curve of the PGI 830 gauge according to the manufacturer's specification [4]

Figure 3. A gauge response assessment and an exclusion of the gauge block form deviations (not drawn to scale)

III. Repeatability of calibration results

In order to evaluate the repeatability of the obtained calibration coefficient Z values, the whole procedure mentioned above has been repeated 10 times, while the calibration setup parameters listed in Table 1 have been applied. The achieved results are presented in Table 2 (α angles) and Fig. 4 (calibration coefficients Z). The α_1 and α_2 angles refer to the slopes of the straight lines fitted to the registered data sets.

Table 2 Calculated values of α angle

No.	1	2	3	4	5	6	7	8	9	10
α_1 [°]	-0.017	0.009	-0.007	-0.005	-0.029	0.002	0.013	0.001	0.018	0.017
α_2 [°]	14.422	14.424	14.413	14.418	14.433	14.404	14.405	14.405	14.406	14.405
α [°]	14.405	14.433	14.406	14.413	14.404	14.406	14.418	14.406	14.424	14.422

The calibration coefficient Z value is very stable within each repetition of a calibration procedure as the relative

differences do not exceed the tenth of a percent. This divergence of results is quite low when compared with other calibration procedures performance. In example, the calibration with a use of the precision hemisphere standard gives the calibration coefficient deviations exceeding 1% [5], what still has been perceived as acceptable, especially when the impact of other factors influencing the uncertainty of surface texture measurements has been taken into consideration.
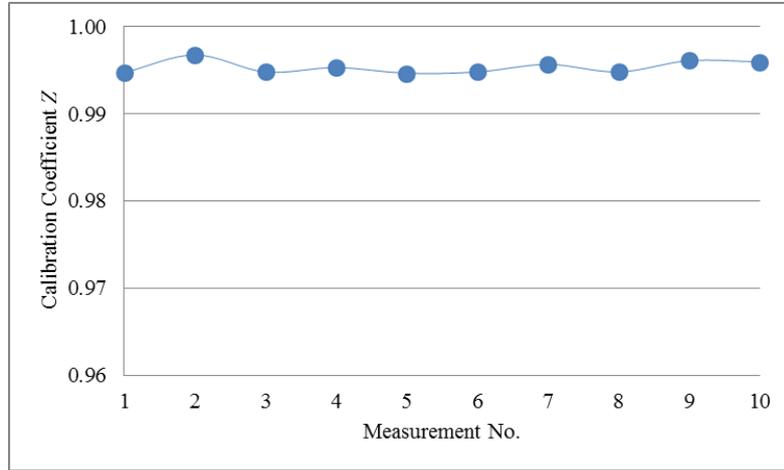

Figure 4. Calibration coefficient Z values

IV. The uncertainty of the proposed method

Also, the uncertainty of the proposed calibration method has been estimated according to GUM recommendations [6]. The first step of determining measurement uncertainty is to define a mathematical model, which includes all variables the measurand may be affected by. Therefore, factors influencing the measured angle α have been set out. Among them there are an angle established with a sine bar α_s and bias associated with the instrument and sine bar configuration ΔE. An impact of temperature variation (20±0.1 °C) and the effect of drift have not been considered, as earlier research has shown that their influence is insignificant [7]. So, the mathematical model is as follows:

$$\alpha = \alpha_s + \Delta E \qquad (3)$$

As it is showed (Eq. 4) the combined standard uncertainty of the measured angle α depends on the angle at sine bar $u(\alpha_m)$ and the standard uncertainties associated with the variability of the measured angles $u(\Delta E)$.

$$u(\alpha) = \sqrt{u^2(\alpha_s) + u^2(\Delta E)} \qquad (4)$$

The α_s angle depends on the trigonometric relation between sine bar length L and gauge block (5) nominal length N_5 (Eq. 5). Due to this, there is relation between the uncertainty $u(\alpha_s)$ and uncertainties of sine bar $u(L)$ and gauge block $u(N_5)$, as outlined in Eq. 6.

$$\alpha_s = arcsin\left(\frac{N_5}{L}\right) \qquad (5)$$

$$u(\alpha_s) = \sqrt{\left(\frac{\partial \alpha_s}{\partial N_5}\right)^2 \cdot u^2(N_5) + \left(\frac{\partial \alpha_s}{\partial L}\right)^2 \cdot u^2(L)} \qquad (6)$$

Then, the uncertainty budget referring to the conducted experiment has been created. It is shown in Table 3.
The research has shown that an impact of the gauge block nominal length and sine bar length is negligible, when compared to a bias caused by the instrument and sine bar configuration. Also, it has been found out that the expanded uncertainty of the measured angle α does not exceed parts of minutes. Due to this, the expanded uncertainty of the calibration coefficient Z does not exceed thousand parts (a few per mills).

Table 3. The uncertainty budget

Source of uncertainty	Estimation	Half-width	Type	Multiplier	Standard uncertainty	Sensitivity coefficient	Results
X_i	x_i	$0.5R_i$	A or B	k	$u(X_i)$	c_i	$u_i(Y)$
N_5	25.000 mm	$6 \cdot 10^{-7}$ mm	B	$\sqrt{3}$	$3.46 \cdot 10^{-7}$ mm	0.0026	$3.58 \cdot 10^{-9}$ rad
L	100.000 mm	$5 \cdot 10^{-7}$ mm	B	$\sqrt{3}$	$2.89 \cdot 10^{-7}$ mm	0.0103	$7.45 \cdot 10^{-10}$ rad
ΔE	0.000				$5.56 \cdot 10^{-5}$ rad	1	$5.56 \cdot 10^{-5}$ rad
Combined standard uncertainty						$u(\alpha) = 11.473$ "	
Expanded uncertainty (P = 0.95)			$k = 2$			$U(\alpha) = 22.95$ "	

V. Conclusions

It has been shown that a stylus profilometer calibration method with a use of a sine bar and gage blocks may have the following advantages over methods that are normalised or popularised by the instruments' manufacturers:

- *Simple.* The introduced calibration procedure is easy and does not require any special preparations.
- *Fast.* The procedure consists of just two simple steps. As it has been mentioned, no extra operations have to be made.
- *Cost-effective.* All accessories essential to perform the calibration are common equipment of each and every metrology laboratory. There is no need to buy any additional standards or devices.
- *Versatile.* In stark contrast to other methods, such as calibration with the precision hemisphere standard, it is not limited to one-instrument usage. Also, it gives a user ability to obtain the gauge characteristics of a wide measuring range instruments.
- *Comprehensive.* Not only does the method enables a user to calculate the calibration coefficient value, but above all, it provides him with detailed information concerning the gauge performance.
- *Easy to be interpreted.* Even a user without advanced and comprehensive knowledge is able to analyse and interpret the calibration results properly as the measurement results are presented in an intuitive way. Also, an estimation of the calibration uncertainty does not cause significant problems.
- *Repeatable.* As the research has shown the method guarantees quite good repeatability of the calculated calibration coefficient values. The relative deviations are not larger than the parts of a percent.
- *Accurate.* Since there is an opportunity to exclude a signal referring to the form deviation of a standard from the gauge characteristics, one of the most important factors affecting the measurement uncertainty is severely limited, and thus more accurate calibration coefficient values can be obtained.

All the reasons mentioned above prove that the introduced method of profilometer calibration is worth-popularising. However, further research is required in order to evaluate applicability of the proposed procedure, when the chosen nominal angle α_n is smaller or the performance of a short range measuring machine is investigated.

VI. References

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