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A COMPARATIVE ANALYSIS OF DIFFERENT METHODS OF SURFACE PLATES FLATNESS CALIBRATION

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Abstract:
This paper describes a comparative overview of different methods of surface plates flatness calibration in the accredited Calibration Laboratory MAGAT Tech. A parallel analysis of methods, together with calculation of the measurement uncertainty, will be presented in detail in this paper. The conclusion of the paper refers to the authors position for the application of the most suitable calibration method of surface plates used in industry, taking into account the measurement uncertainty of calibration and the statement of conformity, in accordance with the level of risk and the requirements of the customer.

Keywords: calibration, flatness, surface plates, conformity, level of risk

1. INTRODUCTION

The research shows there is a lot of professional literature that deals with the methods of surface plates flatness calibration, e.g. [1], [2] and that is a fully known and researched area. Measurement uncertainty calculation of surface plates calibration has been also processed by some papers, e.g. [3] and [4]. The main reason for writing this paper is to introduce the most suitable method of surface plates flatness calibration, commonly used in industry, when giving the statement of conformity. Comparing the different methods and their measurement uncertainty, the question arises whether the calibration method depends on reporting the statement of conformity with specification, taking into account the level of risk.

2. METHODS OF CALIBRATION

MAGAT Tech, Calibration Laboratory (hereinafter the Laboratory) is accredited laboratory according to ISO/IEC 17025:2017 [5], by Accreditation Body of Serbia (ATS), the signature of ILAC MRA agreement.

Most commonly known methods of surface plates flatness calibration refer to calibration by a laser interferometry, autocollimator and electronic level.

The methods used by MAGAT Tech accredited Calibration Laboratory are methods of calibration by an optical measuring device and by an electronic level. The methods of calibration by a laser interferometry and by an autocollimator are also used in the Laboratory, but not in routine calibrations for industry, due to high accuracy of methods and inefficiences for the stated needs.

2.1 Calibration by an optical measuring device

Calibration by an optical measuring device (for measuring of straightness) is used at surface plates dimensions over 1000 mm up to 1600 mm: see Figure 1. Calibration is performed at the Laboratory and on site.

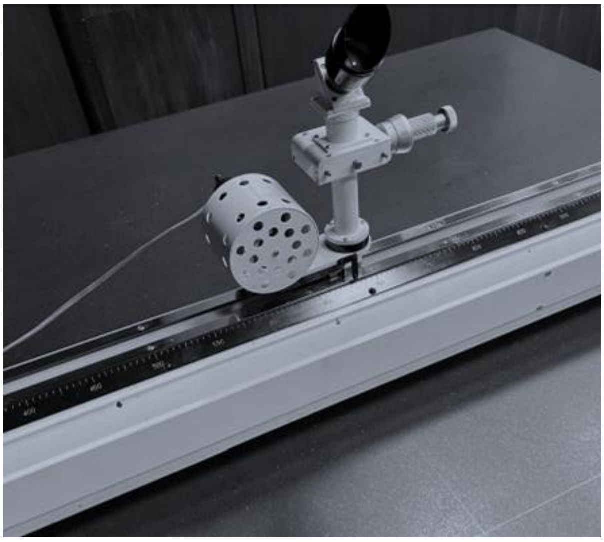

Figure 1: Calibration by optical measuring device (for straightness)

The optical measuring device, model IS-36, works on principle shown in Figure 2. The measurement probe of the device is brought into the appropriate measurement point marked on a surface plate (measurement grid). Then it is optically positioned via the cross-line mark and a height deviation is read by means of the micrometer screw [8]. The overall flatness of a surface plate is calculated manually or with licenced flatness measurement software [9].

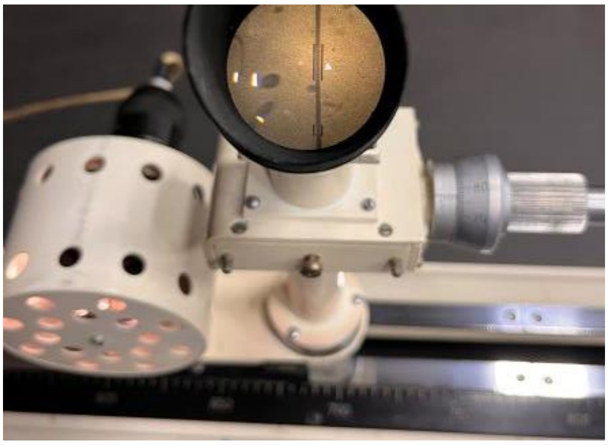

Figure 2: The working principle of optical measuring device IS-36

According to [11], influence of all impact parameters to measurement uncertainty are given by equation (1).

$$y = f\left(x_1, x_2, x_3, \ldots, x_n\right). \tag{1}$$

The uncertainty budget for calibration by the optical measuring device is given in Table 1, where:

l_s – Contribution of standard (measurement equipment),

ΔT_{dut} – Influence of temperature deviation on surface plate,

Δt_{amb} - Influence of temperature deviation from 20°C on measurement equipment,

δl_{res} – Influence of resolution of measurement equipment,

δl_{fok} - Influence of optical device of measurement equipment.

Table 1: The uncertainty budget for calibration by the optical measuring device (ex. for the height deviation of 2 µm)

Quantity X_i	**Standard uncertainty** $u(x_i)$	**Probability distribution**	**Sensitivity coefficient** c_i	**Uncertainty Contribution** $u_i(y)$
l_s	0.75 µm	Normal	1	0.75 µm
ΔT_{dut}	0.12 K	Rectangular	$11.2\cdot10^{-6}$ µmK^{-1}	$1.34\cdot10^{-6}$ µm
Δt_{amb}	0.29 K	Rectangular	$23\cdot10^{-6}$ µmK^{-1}	$6.67\cdot10^{-6}$ µm
δl_{res}	0.29 µm	Rectangular	1	0.29 µm
δl_{fok}	0.06 µm	Rectangular	1	0.06 µm
l_x			u_c	0.81 µm

2.2 Calibration by an electronic level

Calibration by an electronic level is used at surface plates dimensions over 630 mm: see Figure 2. Calibration is performed at the Laboratory and on site.

Calibration by the electronic level, model DL-S3, works on principle of shifting the electronic level along the measurement directions of the measurement grid, so called 'spider web' and reading the slope of the marked surface plate segment. The overall flatness of a surface plate is calculated by licenced flatness measurement software [9].

The uncertainty budget for calibration by the electronic level is given in Table 2, where:

l_s – Contribution of standard (measurement equipment),

ΔT_{dut} – Influence of temperature deviation on surface plate,

Δt_{amb} - Influence of temperature deviation from 20°C on measurement equipment,

δl_{res} – Influence of resolution of measurement equipment,

δl_{pos} - Influence of positioning of measuring device.

Here, the positioning of the electronic level on the corresponding measurement point, has a big influence on the measurement uncertainty.

Figure 2: Calibration by the electronic level

Table 2: The uncertainty budget for calibration by the electronic level (ex. for 150 mm segment and slope 13 µm/m)

Quantity X_i	**Standard uncertainty** $u(x_i)$	**Probability distribution**	**Sensitivity coefficient** c_i	**Uncertainty Contribution** $u_i(y)$
l_s	0.75 µm	Normal	1	0.75 µm
ΔT_{dut}	0.12 K	Rectangular	$11.2\cdot10^{-6}$ µmK^{-1}	$1.34\cdot10^{-6}$ µm
Δt_{amb}	0.29 K	Rectangular	$23\cdot10^{-6}$ µmK^{-1}	$6.67\cdot10^{-6}$ µm
δl_{res}	0.09 µm	Rectangular	1	0.09 µm
Δl_{pos}	0.17 µm	Rectangular	1	0.17 µm
l_x			u_c	0.77 µm

Calibration for surface plates dimensions up to 630 mm is not possible by an optical measuring device. The optical measuring device used in the Laboratory cannot be set physically on a surface plate of these dimensions. At the other hand the electronic level, due to the dimension of base 150 mm, does not have a sufficient number of measurement points for calibration. The Laboratory has developed the method of calibration surface plates dimensions up to 630 mm by the electronic level put on sine bar, which achieves the base length of 100 mm.

The uncertainty budget for this calibration is the same, see Table 2.

3. TYPES OF SURFACE PLATES

The requirements of surface plates are described in standards, for example DIN 876, part 1 for hard rock surface plates and part 2 for cost iron surface plates. The most commonly surface plates used in industry are of class 0, 1 or 2.

The flatness tolerances according the DIN 876-1 are given in Table 4: see [6].

Table 4: Values for tolerances according to DIN 876-1:[6]

Length l (mm)	**Flatness tolerances for accuracy grade** (µm)		
	0	1	2
160	5	12	24
250	5	13	25
400	6	14	28
630	7	17	33
1000	8	20	40
1600	11	26	52
2000	12	30	60
2500	14	35	70

4. STATEMENT OF CONFORMITY AND LEVEL OF RISK

MAGAT Tech Calibration Laboratory provides the statement of conformity, on customer requirement, according to tolerances given in standards for surface plates, DIN 876-1 and DIN 876-2.

The decision rule used by the Laboratory, when providing the statement of conformity, is based on the ILAC-G8:09 guideline, see [10]. Two decision rules are used: Simple acceptance rule: see p. 9 of [10] and Non-binary Statement with Guard Band: see p.10 of [10].

When using Simple rule, no measurement uncertainty is taking into account. The risk of accepted item to be outside of the tolerance limit is up to 50%. The risk of false reject is also up to 50% [10].

When using Non-binary rule, specification limits are reduced by the guard band. As the guard band is equal to the expanded measurement uncertainty of calibration U (k=2), acceptance interval depends on the measurement uncertainty of calibration. The expanded measurement uncertainty of calibration shall not be larger than 1/3 of tolerance limits. In this case, the risk of accepted item to be outside of the tolerance limit is less than 2.5%. The risk of false reject is also less than 2.5%. When the measured result is close to the tolerance (Conditional Pass/Conditional Fail), the risk of false accept and false reject is up to 50% [10].

5. THE CHOICE OF METHOD AND DECISION RULE

The choice of appropriate method of calibration first of all depends of length of calibrated surface plate (shown in section 2 of this paper). Considering that calibration could be performed on site, the choice of appropriate method also depends of position of a surface plate at the place of use. For example, a surface plate can be placed in corner of the room or near the column. In that case, using the optical measuring device is almost impossible. The other problem refers to levelling a surface plate. If a surface plate is not levelled, an electronic level could be out of the measuring range. All previously said affects the choice of appropriate method. That is why the Laboratory should have more than one method of calibration, in order to provide all customer requirements.

For example, the granite surface plate, grade 0, length 1600 mm, in MAGAT Tech Laboratory, could be calibrated by two different methods: by the optical measuring device IS-36 and by the electronic level DL-S3. The expanded measurement uncertainties of both methods are almost the same and at the same time less than 1/3 of tolerance limits of specifications given in corresponding standards (shown in section 3 of this paper, Table 4). The results and expanded measurement uncertainties for both methods are given in Table 5.

Table 5: Example of a result of a measurement (1600 mm surface plate)

Method of calibration	**Flatness**	**Measurement uncertainty *U (k=2)***
Optical measuring device	9.5 µm	1.7 µm
Electronic level	9.6 µm	1.5 µm

In this example, the results obtained by both methods are practically the same and the difference of measurement uncertainty is very small. Measurement uncertainty is less than 1/3 of tolerance limits of specifications. So, the both methods could be used and choice does not depend on defined decision rule. As the measured value is in tolerance with both methods, using Simple decision rule, the statement of conformity is reported as Pass. When using Non-binary decision rule, the measurement results for both methods are outside the acceptance limit, but inside of tolerance limit. In this case, the statement of conformity is reported as Conditional Pass. See graphical presentation in figure 3. The level of risk, in both cases, are the same, up to 50%, see Table 6.

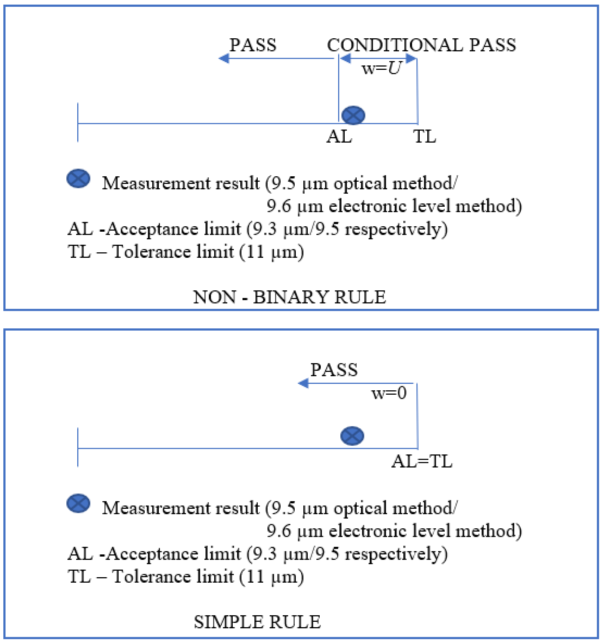

Figure 3: Graphical presentation of decision rules for 1600 mm surface plate

Another example, for granite surface plate grade 0, length 630 mm, is given in Table 7. The method is chosen according to length of surface plate (electronic level and sine bar). Method with optical measuring device could not be used in such case, due to the size of surface plate (see 2.1). Also, the method with electronic level (base 150 mm) could not be used in this case, due to the insufficient measurement points. So, for surface plates up to 630 mm, the comparison of methods is not applicable. The expanded measurement uncertainty of chosen method is also less than 1/3 of tolerance limits (7 µm) and the obtained flatness is in acceptance interval.

Table 7: Example of a result of a measurement (630 mm surface plate)

Method of calibration	**Flatness**	**Measurement uncertainty *U (k=2)***
Electronic level	3.5 µm	1.5 µm

In such case, this method is the only one applicable and also does not depend on defined decision rule, due to the appropriate measurement uncertainty. When using the Simple rule, the statement of conformity is reported as Pass, with level of risk up to 50 %. When using the Non-binary rule, the statement of conformity is reported also as Pass, but with level of risk up to 2.5 %. See graphical presentation given in figure 4.

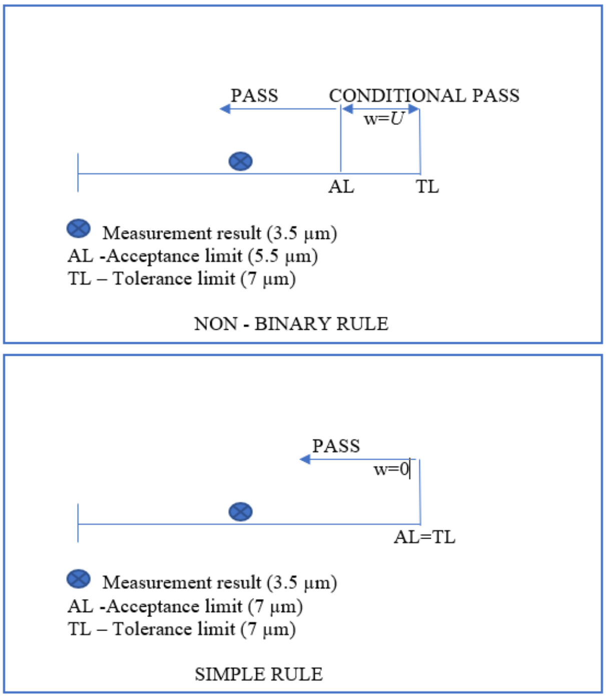

Figure 4: Graphical presentation of decision rules for 630 mm surface plate

Table 6: Statement of conformity (the 1st example)

Surface plate	Method of calibration	Flatness	Acceptance limit	Statement of conformity	
Length: 1600 mm Accuracy grade: 0 Flatness tolerance: 11 µm	optical measuring device	9.5 µm	9.3 µm	Simple rule (50% risk)	PASS
				Non-binary rule with Guard Band (50% risk)	CONDITIONAL PASS
	electronic level (base 150 mm)	9.6 µm	9.5 µm	Simple rule (50% risk)	PASS
				Non-binary rule with Guard Band (50% risk)	CONDITIONAL PASS

Table 8: Statement of conformity (the 2nd example)

Surface plate	Method of calibration	Flatness	Acceptance limit	Statement of conformity	
Length: 630 mm Accuracy grade: 0 Flatness tolerance:7 µm	electronic level (base 100 mm)	3.5 µm	5.3 µm	Simple rule (50% risk)	PASS
				Non-binary rule with Guard Band (2.5% risk)	PASS

In the example given in Table 6., the both statements are given with the level of risk of 50%. In the example given in Table 8., the both statements are the same, but the different level of risk (50% and 2.5%).

Problem arises when the customer requests the statement of conformity and does not understand the decision rule (such as Conditional pass) and the level of risk the Laboratory provides. In that case, the Laboratory shall educate the customer in such a way to give the customer the best solution for him and at the same time to preserve its impartiality.

Simple acceptance rule should be used, when the statement of conformity is given with the same level of risk, e.g 50% (see Table 6). When the statement of conformity is the same, e.g PASS, but with different level of risk (see Table 8), Non-binary decision rule should be used because of the smaller level of risk, if the measurement uncertinty of the calibration method alows it.

6. SUMMARY

For the surface plates used in industry (grade 0, 1 or 2), efficient calibration methods refer to the two different methods: by an optical device and an electronic level (with different length of base). First of all, the choice among them depends on the size of calibrated surface plate. For surface plates up to 630 mm, there are some limitations and only one method, from methods shown and explained in this paper, could be used. For surface plates higher than 630 mm, both methods explained in this paper, could be used. If the customer requests statement of conformity with specification, the choice between methods depends on the measurement uncertainty of calibration in regard to the requested decision rule. The expanded measurement uncertainty of calibration must be less than 1/3 of tolerance limits, for using Non-binary decision rule. It is shown in this paper that MAGAT Tech calibration laboratory has the measurement uncertainty of all methods less than 1/3 of flatness tolerances for all surface plates grades and dimensions.

Precisely because of this, accredited calibration laboratories have difficult task to provide measurement methods with small expanded maesurement uncertainty.

The measurement uncertainty of calibration and requested decision rule is not the only parameter that defines the calibration method for surface plates flatness calibration. It depends also on the length of surface plate, conditions for on-site manipulations and efficiency of calibration.

Some methods, with autocollimator and laser interferometer, with small measurement uncertainty, are not efficient for calibration on-site, in industry and that is way these methods were not discussed in this paper.

When comparing the optical measuring device method with the electronic level method, in case studies given in this paper, it is concluded that due to almost the same and corresponding measurement uncertainty, decision rules have no influence on the choice of methods, when giving a statement of conformity.

The advantages of the optical device are an easier calibration process and a reduction of the uncertainty parameter due to positioning of measuring instrument. However, due to its dimensions, it is difficult to transport to the site, as well as on-site manipulation, if the position of the surface plate is not free for the movement of the operator.

The advantages of electronic level are easy transportation and manipulation on-site. With appropriate base it could be used for all surface plates lengths. The disadvantage of this method refers to levelling of a surface plate.

As far as decision rules are concerned, due to corresponding measurement uncertainty of calibration, both methods could be used for both decision rules described in this paper.

In regard to everything previously processed, the authors opinion is that, despite all limitations due to problems with levelling of surface plate, the best solution is using the method of calibration by an electronic level, for all dimensions and grades of surface plates used in industry.

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