Methods of Union Jack and XY-Grid in Surface Plate Measurements

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Abstract

Surface plates are considered main tools in production metrology. It acts as reference planes for different measurements of heights and depths. The flatness errors, which are the main geometrical errors of surface plates, should be determined in the right ways. There are several methods and high-precision instruments that can be used in measurements of such errors. In this study, two union-jack and xy-grid measurement methods are used to calibrate grade 1 granite surface plate. The number of measured lines differs from one Method to the other. While it is stated as eight lines for the union-jack Method, it is ranged from 10 to 12 lines for xy-grid method with line steps of 100 mm. The flatness errors of a plate are determined through straightness measurements of these lines. The number of measured lines strongly affects the determined flatness errors. Flatness errors and associated uncertainties by different methods are analyzed, evaluated and compared. The calibration by the xy-grid method gives a strong and real representation of flatness errors of the surface plate.

Article Highlights: this paper studies the common strategies used in calibration of surfae plate; Union Jack and XY-Grid methods. The number of test points, lines and regions are changed according to the method used. The calibrations are carried out four times by each method. In each time; the starting corner is changed. Measurement results and associated uncertainties in these eight calibrations are compared.

Keywords: *Flatness measurements, Surface plates, Autocollimator, Union-Jack, XY-Grid*

1. Introduction

Surface plates are necessary for different applications in dimensional and production metrology [1]. These applications can include calibration of height check masters, height gauges, and measurements of the heights of manufactured products [2]. These plates have different material types: granite, steel, and cast iron. Surface plates have a wide range of surface sizes, ranging from tens of millimeters up to several meters with circular, rectangular, and square surface shapes [3]. The plates are used correctly through two issues: (1) level adjusting of the plate, which can be done by using a highly precise digital or spirit level; (2) Measurements of the flatness errors of its upper surface Flatness error is an independent geometrical feature defined in many standards as the minimum distance between two parallel planes so that all measurement points describing the surface lie between the two plans [4, 5]. The flatness errors can be measured by mapping the surface plate according to the specified test method. The union-jack and xy-grid are the most common methods used in this measurement type. In each method, the surface plate is mapped to a certain number of lines, and the straightness errors are measured for each line [6, 7]. The plate's flatness errors are determined depending on the straightness errors of these lines. The number of measured lines and straightness errors in each strongly influence the determined flatness errors [8]. The mathematical algorithm that is used in the determination of flatness errors should be precisely chosen. There are different precise instruments that can be used for flatness measurements of surface plates [9]. One of the most accurate instruments is the autocollimator, which can measure flatness errors with accuracy up to 0.05 arcs [10–11]. In this paper, an autocollimator system of 0.05 arcs of accuracy with a step size of 100 mm is used in the measurement of flatness errors of a grade 1 granite surface plate. The methods of union-jack and xy-grid are used. The plate is calibrated by each method four times, and each time the start corner is changed. The flatness measurements in these eight times are analyzed by two algorithms: least squares fitting and minimum zone methods [12]. The associated uncertainties in each calibration are determined [13–14]. In the next section, descriptions of measuring instruments, methods, and measurement procedures are presented. In Section 3, the measurement results and evaluation of uncertainties are presented. In Section 4, the results are discussed under different measurement conditions. In Section 5, the main conclusions are outlined.

2. Methods and Procedure

In this work, an autocollimator system with a resolution of 0.05 arcs is used. It is used for flatness measurements on grade 1 granite surface plates. The plate has a surface size of 750 mm by 1000 mm. The calibration is carried out by two methods: Union-Jack and XY-Grid. The surface plate is calibrated four times by each method, where each time the start corner is changed.

2.1. Autocollimator System

The Autocollimator is an optical instrument that measures the small angular displacements of a mirror or other suitable reflecting surfaces [14]. The image of an illuminated object located in the rear focal plane of the collimator lens is projected to infinity and reflected via a mirror, as in Figure 1. The image is picked up by a light sensitive receiver. A slight alteration of the angle between the optical axis of the autocollimator and the mirror causes a deviation which can be determined very precisely. The electronic autocollimator type provides measurement of smallest deviation of inclination in two orthogonal axes in fractions of arc seconds. This optical design of autocollimator can be used for measurements of straightness and flatness, Figure 2.

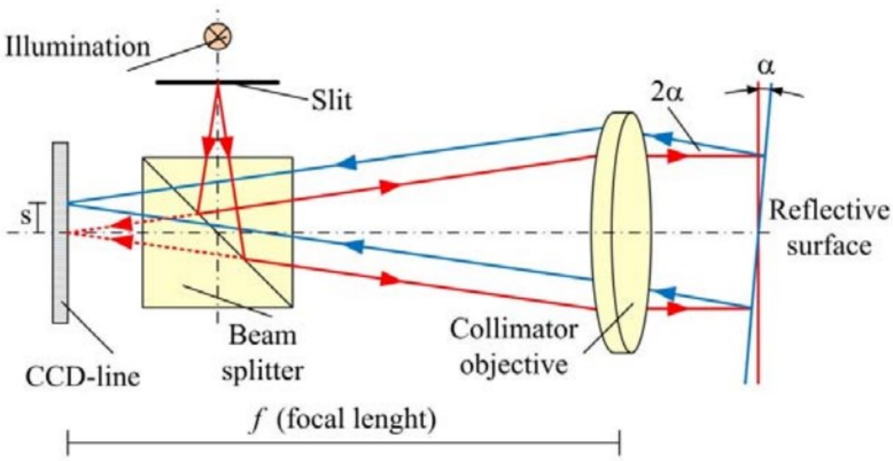


Figure 1: measurement principle by autocollimator system [14].

Figure 2: Flatness measurements by autocollimator system

2.2. Union-Jack Method

It is one of most common methods that are used in calibration of surface plates, Figure 3. The plate is mapped into eight lines (generators); three parallel to long side, three parallel to short side and two diagonals of the plate. Each line is divided into equal steps of 100 mm. There are guide arrows for straightness measurement of each line. The straightness of each line is measured through measuring difference in heights at each point on each line. By analysis of straightness results from all lines, the flatness deviation of the surface plate is determined.

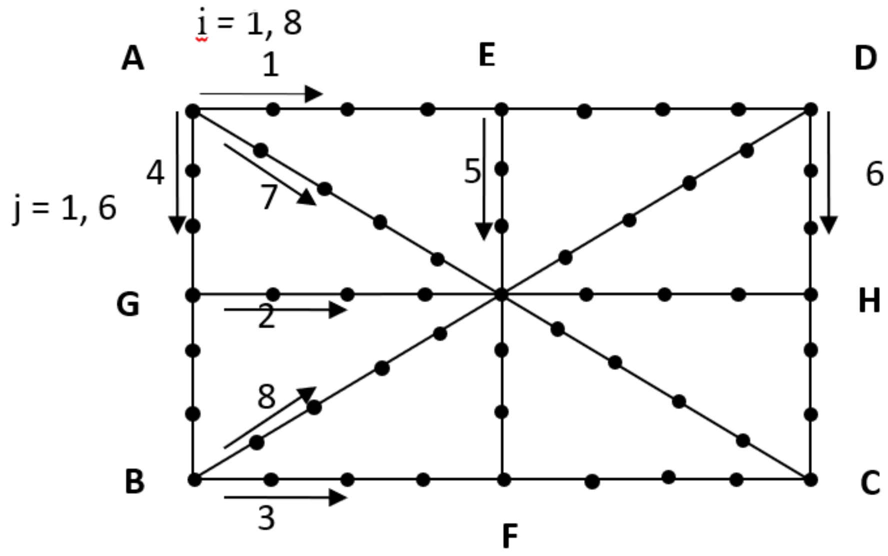
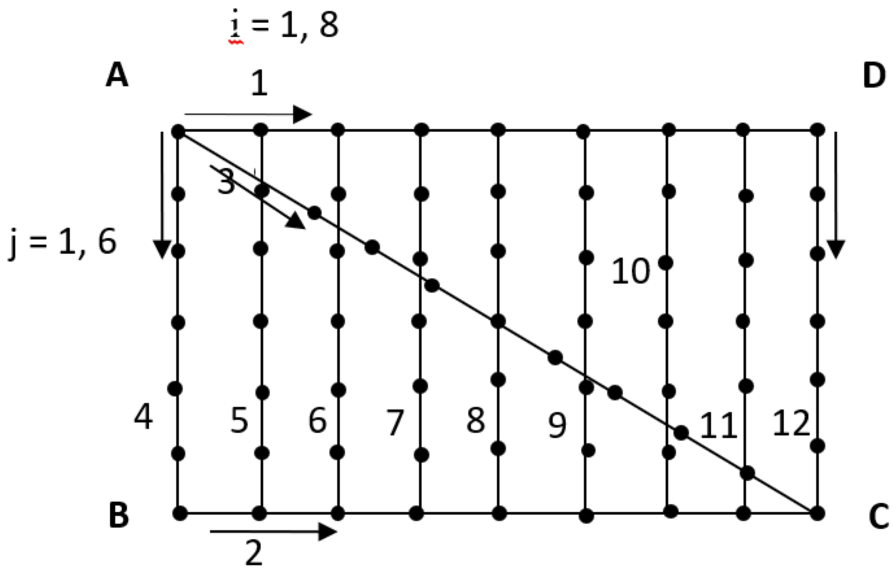


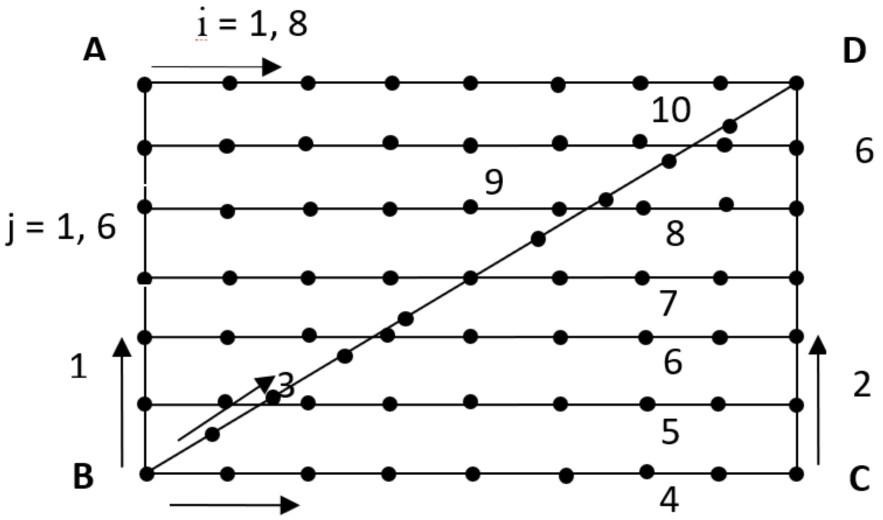
Figure 3: Union Jack Test Pattern for granite surface plate (600×800 mm)
(i, j, represent position of the step on the particular generator)
(Numbers on arrows are the order of performing measurements)

2.3. *XY-Grid Method*

This method consists of number of lines depends on the direction of measurements and step distance between selected lines. In general, there two lines parallel to long side, two lines parallel to short side, one diagonal of the plate and some entire lines parallel to one of plate sides with equal distances. Each line is divided into equal steps of 100 mm. There are guide arrows for straightness measurement in each line, Figures 4.



a. 12 lines



b. 10 lines

Figure 4: XY-Grid Pattern for granite surface plate (600×800 mm), a and b.
(i, j, represent position of the step on the particular generator)
(Numbers on arrows are the order of performing measurements)

2.4. Measurement Procedure

The flatness deviation of the surface plate is determined in four steps. (1) The plate under calibration is mapped to a number of lines according to the selected method i.e. union jack or xy-grid method. (2) Each line is divided into equal steps of 100 mm. (3) the straightness of each line is measured through measuring difference in heights at each point. (4) From results of all measured points the flatness of the plate can be determined.

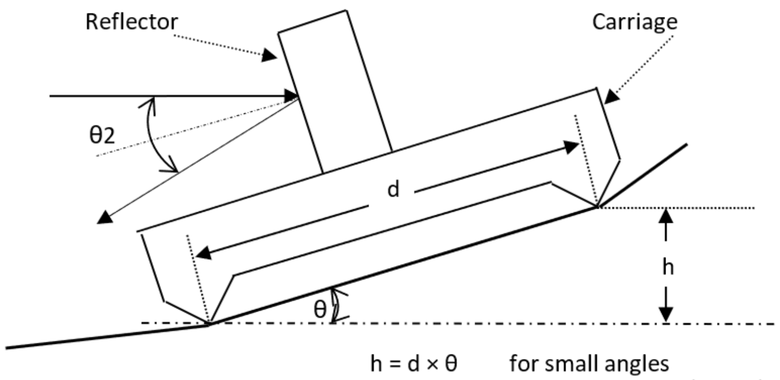


Figure 5: Angular variation of carriage at measured point on tested plate

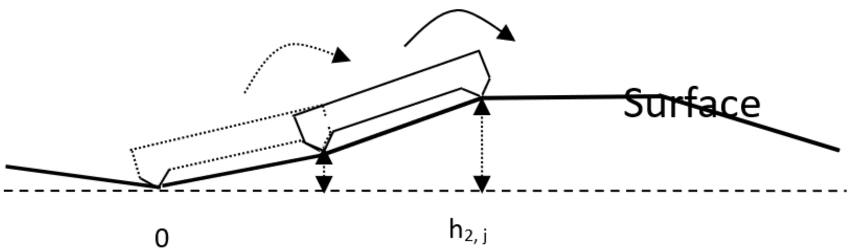


Figure 6: The carriage is stepwise moved over the tested plate.

The measurements of straightness at each point depend on the measuring instruments that are used (Figure 5). For autocollimator systems, the straightness deviations are measured based on the inclination method. The angular variations at measured points are measured and then turned into heights. The reflecting unit (the reflecting mirror in the autocollimator) is placed on a carriage that has two contact flat feet, with a separation distance equal to the dividing step of each line. The light source (autocollimator head) placed on a tripod is aligned with the reflecting unit. At the beginning of measuring the straightness of each line, the reflecting unit is moved to the first step to reset the measuring system at this position.

The carriage is moved to the next step to indicate angular variations in comparison to the first position. By using the same method, the angular variations at each measured point in each line can be measured, and the same is true for all measured lines. The heights (h) at measured points are determined by multiplying the angular variations () by the feet step of the carriage (d = 100 mm), as shown in Figure 6. All measured points are fitted to a reference plane and analyzed to calculate the flatness deviation of the measured plate. The flatness measurements can be analyzed by two methods: regression (the least squares method) and ISO 1101 (the minimum zone method).

3. Experimental Results

The results for flatness measurements using the two methods, union-jack and xy-grid are presented.

3.1. Union-Jack Method

The plate has four corners denoted by A, B, C and D. The surface plate is calibrated through four calibrations using one of these corners as a starting position (corner)–each time. The measurement results are presented in Table 1 and Figure 7.

Table 1: Flatness measurements by Union-Jack Method

Start Corner	Measurement technique	Out of flatness, µm	
		Analyzed by Minimum Zone	Analyzed by least square
A	Union-Jack Method	9.43	9.93
B		10.56	11.27
C		11.05	11.63
D		10.29	11.97

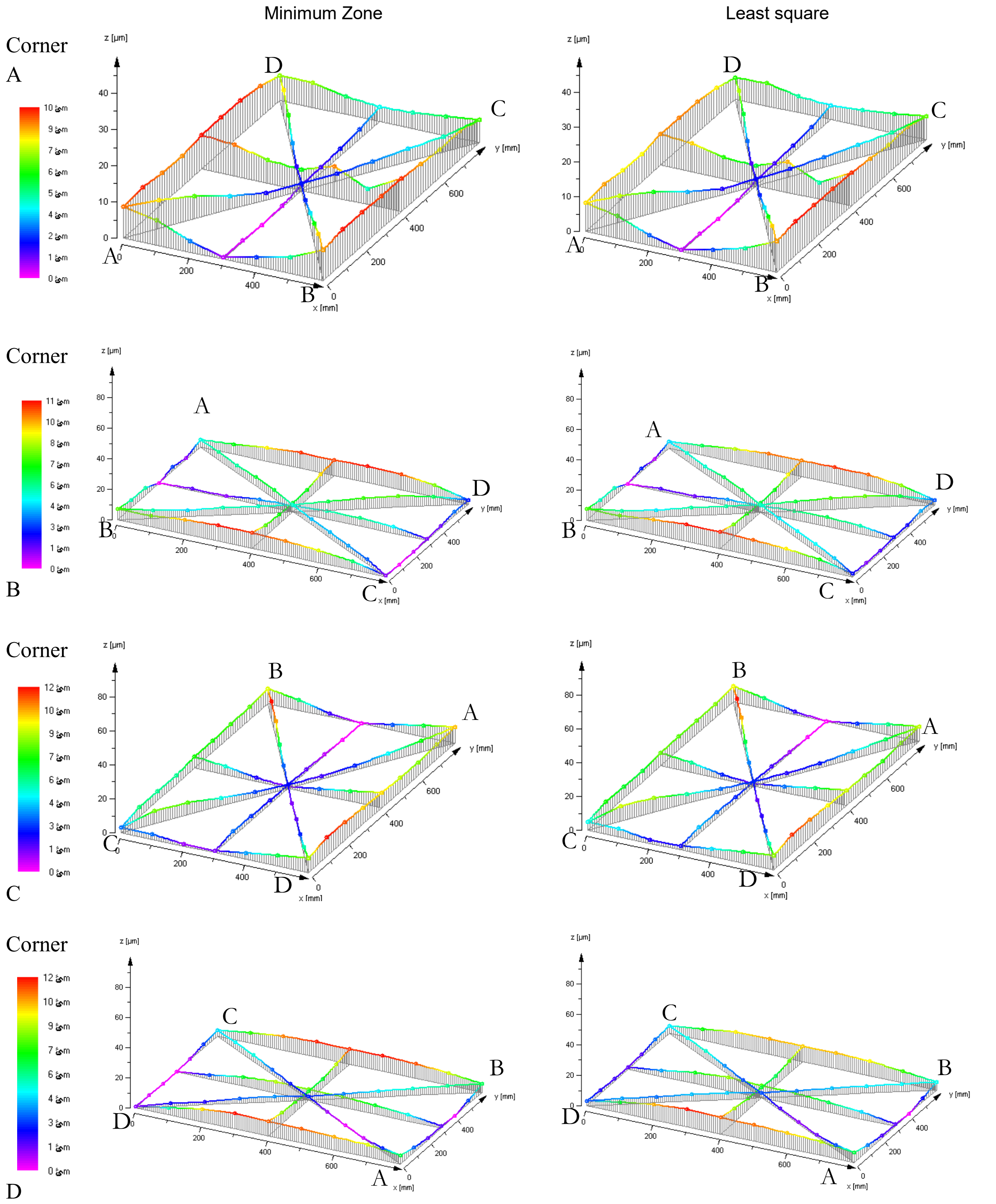


Figure 7: Surface Plate Calibration Using Union-Jack Method at different starting corners

3.2 XY-Grid Method

The granite surface plate is calibrated using XY-Grid method through 10 and 12 lines depending on the starting corners in each calibration time. The measurement results are presented in Table 2 and Figure 8.

Table 2: Flatness measurements by XY-Grid method

Start Corner	Measurement technique	Out of flatness, µm	
		Analyzed by Minimum Zone	Analyzed by least square
A	XY-Grid Method	11.93	11.29
B		11.44	11.94
C		10.38	11.10
D		8.71	9.80

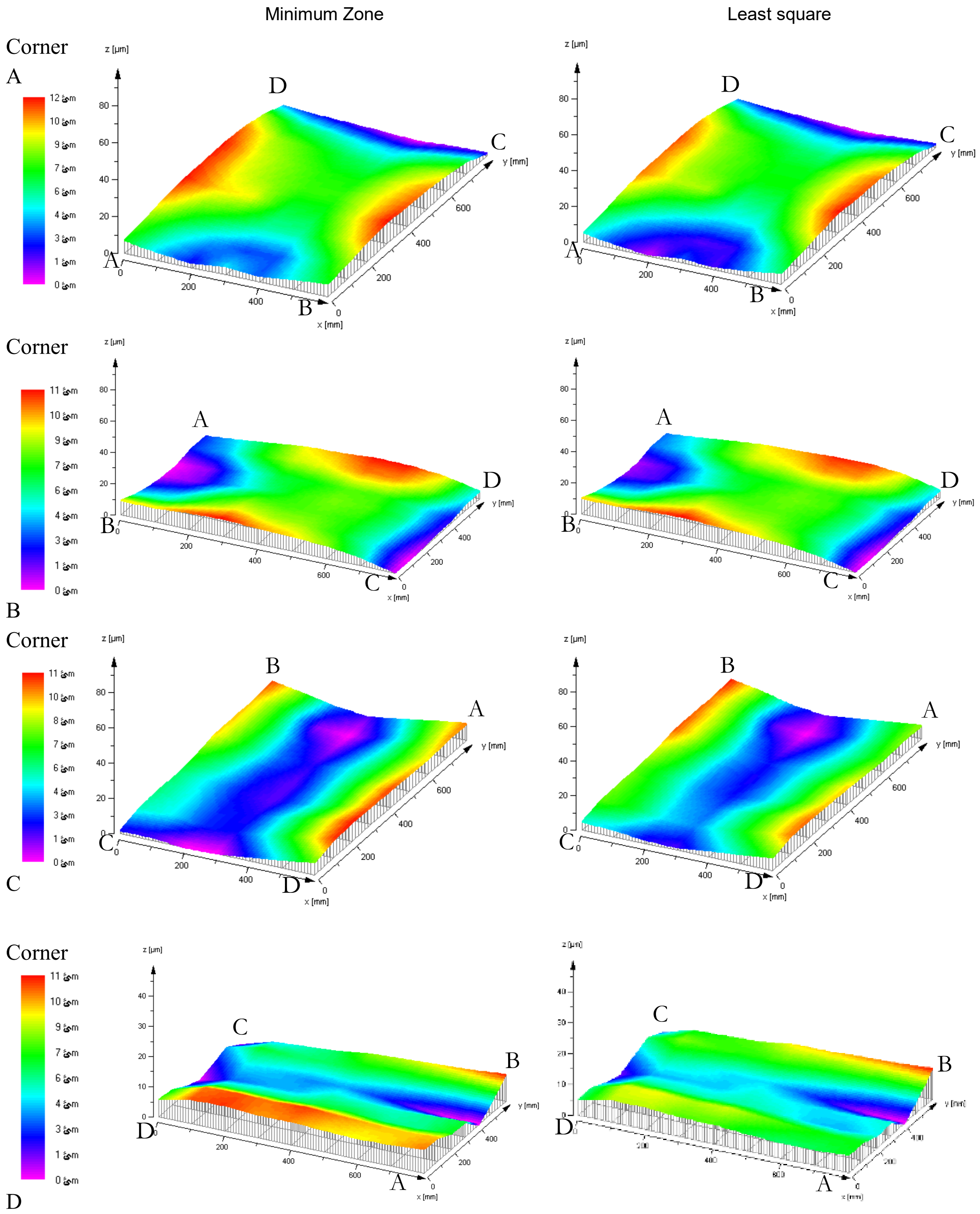


Figure 8: Surface Plate Calibration Using XY-Grid Method at different starting corners

3.3. Uncertainty Evaluation

The associated uncertainties in surface plate calibration are evaluated based on GUM [10]. The random source type A evaluation of uncertainty depends on the repeatability of calibration process of surface plate. The systematic source (type B of uncertainty) depends on the Method used for the assessment of flatness deviation. The flatness deviation using autocollimator systems is based on angular variations (θ) which are observed when a carriage with contact feet separated by a distance (d) is stepwise moved over the tested surface. These angular variations (θ) are then transformed to variation in heights by multiplying (θ) by (d).

Based on [10, 14], The major contributors to the type B uncertainty evaluation are associated with the measured angle at any position u(θ) are expected to be: the stated accuracy of the instrument calibration, instrument resolution, instability of the system due to environmental thermal effects, error in placement of the carriage, error in distance between feet of the carriage, carriage pads contact area and flatness or linearity of reflectors. Other effects such as noise, vibrations could be considered incorporated in calibration of the instrument or small compared to the mentioned contributors. Table 3 represents the evaluation in uncertainty in u(θ) for grade 1 surface plate.

Table 3: uncertainty Budget in measuring the angular deviations θ on grade 1 plate.

Sources of Uncertainty θ_i	$U(\theta_i)$, arcsec	Distribution	Standard Uncertainty $u(\theta_i)$, arcs	Sensitivity factor c_i	associated uncertainty, $u^2(\theta_i)$, arcs	Degree of freedom, ν_i
Instrument calibration	0.05	rectangular	0.03	1	$(0.03)^2$	∞
Resolution	0.025	rectangular	0.014	1	$(0.014)^2$	∞
Instability	0.10	rectangular	0.07	1	$(0.07)^2$	5
Flatness of reflecting mirror	0.10	rectangular	0.06	1	$(0.06)^2$	∞
Placement	0.032	rectangular	0.018	1	$(0.018)^2$	51
Feet spacing	0.047	rectangular	0.027	1	$(0.027)^2$	51
Pad Contact Area	0.01	rectangular	0.006	1	$(0.006)^2$	51
Standard Uncertainty, u(θ) = 0.11 arcs, $\nu_{eff} = \infty$						

The systematic components of uncertainty u(φ) can be evaluated according to the equations [10, 14];

$$u^2(\varphi) = 2\, u^2(\theta)\, (d/2)^2\, [l + m + n],$$

where: *l, m, n* are the number of steps over the long, short and diagonal generators; d distance between carriage feet and u(θ) uncertainty in angle measurements.

The expanded uncertainties of flatness deviation U_φ measurements of the granite surface plate by each Method and at each corner are shown in tables 4 and 5 respectively.

Table 4: Uncertainty budget in surface plate calibration by different test pattern

Type of uncertainty	Union-Jack Method		XY-Grid Method	
	Minimum zone	Least square	Minimum zone	Least square
Type A (standard uncertainty)	$(0.34)^2$	$(0.45)^2$	$(0.71)^2$	$(0.45)^2$
Type B (systematic uncertainty)	$(0.17)^2$	$(0.17)^2$	$(0.22)^2$	$(0.22)^2$

Combined standard uncertainty $u_c(\varphi)$	0.38 µm	0.48 µm	0.75 µm	0.50 µm
Expanded uncertainty, $U_\varphi = 2\ u_c(\varphi)$	0.76 µm	0.96 µm	1.49 µm	1.00 µm
Effective degree of freedom, ν_{eff}	∞	∞	∞	∞

Table 5: Uncertainty budget in plate calibration by each corner as starting point for measurements.

Type of uncertainty	Corner A	Corner B	Corner C	Corner D
Type A (standard uncertainty)	$(0.58)^2$	$(0.29)^2$	$(0.26)^2$	$(0.68)^2$
Type B (systematic uncertainty)	$(0.20)^2$	$(0.20)^2$	$(0.20)^2$	$(0.20)^2$
Combined standard uncertainty $u_c(\varphi)$	0.61 µm	0.35 µm	0.32 µm	0.71 µm
Expanded uncertainty, $U_\varphi = 2\ u_c(\varphi)$	1.23 µm	0.70 µm	0.65 µm	1.41 µm
Effective degree of freedom, ν_{eff}	∞	∞	∞	∞

4. Discussion

4.1Union-Jack and XY-Grid methods

The surface plate is calibrated using two methods: union-jack and xy-grid. In the union-jack method, the straightness of eight lines is measured with a step of 100 mm. The straightness measurements are carried out for 62 points with 8 regions of working areas on the surface plate. In the xy-grid method, the number of measured lines is increased to 10 lines. The number of measured points is 78 and 80, respectively. The covered areas by measurements are increased to 12 and 18 regions, respectively (Table 6).

Table 6. Measured points, lines and areas by each test pattern

	Union-Jack Test Pattern	**XY-Grid Test Pattern**	**Increasing, %**
Measured lines	8	10 – 12	25 – 50 %
Measured Points	62	78 – 80	26 – 29 %
Measured areas	8	12 – 18	50 – 125 %

The flatness errors of surface plates by xy-grid have a higher value in comparison to those by the union-jack method (Figures 7–8). The interpretation of these resulted errors may be due to the increasing number of lines, points, and areas in the xy-grid, which can give a more real representation of the flatness value of the surface plate. The normalizing error number En and error bar for the obtained results by each method are represented in Table 7 and Figure 9. It appears that the results from both methods are consistent.

Table 7. Normalizing error number En for results by both methods

Comparison between results of	**En**	
	Minimum zone	Least square
Union-jack / XY-grid	0.17 (<1)	0.12 (<1)

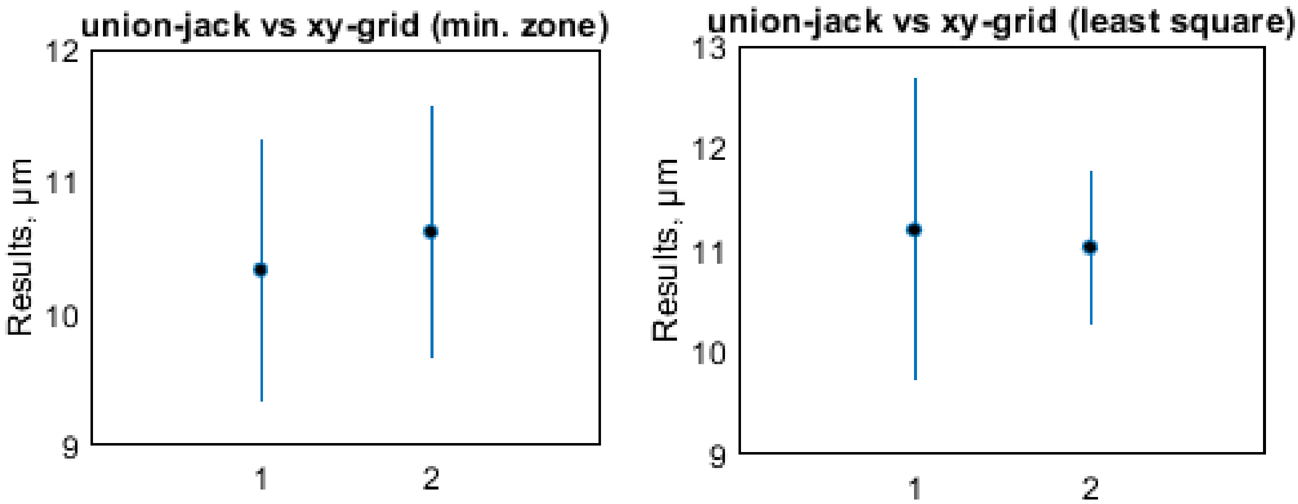


Figure 9. The error bar for results by both test patterns; 1: union-jack, 2: xy-grid

4.1. Starting corners for calibration of surface plate

The flatness measurements are performed 4 times by each Method. In each time, the starting position (corner) is changed, Table 8. It is initially expected that flatness deviation should be not affected by the starting position for surface plate calibration. The experimental results show percentage difference in flatness deviation about 2 – 10 % from position to another, Table 9. This difference should be included in evaluation of associated uncertainty.

Table 8: Flatness measurements of Surface Plate Calibration with different start position

Method	Union Jack		XY Grid		Flatness errors, µm	Expanded uncertainty (U), µm
Start Position	Minimum Zone	least square	Minimum Zone	least square		
A	9.43	9.93	11.93	11.29	**10.65**	**1.23**
B	10.56	11.27	11.44	11.94	**11.30**	**0.70**
C	11.05	11.63	10.38	11.1	**11.04**	**0.65**
D	10.29	11.97	8.71	9.8	**10.19**	**1.41**

Table 9. Percentage difference in flatness deviation at each position

Start position	**Difference, %**					
	A to B	A to C	A to D	B to C	B to D	C to D
	6.2	3.7	4.3	2.3	9.8	7.7

The error bar for the obtained results by each start positions and normalizing error number En is represented in Table 10 and Figure 10. It is appeared that the results by different start positions (corners) are consistent.

Table 10. Normalizing error number En for results by both test patterns at each position

Start position	**En**					
	A to B	A to C	A to D	B to C	B to D	C to D
	0.47 (<1)	0.28 (<1)	0.24 (<1)	0.28 (<1)	0.70 (<1)	0.54 (<1)

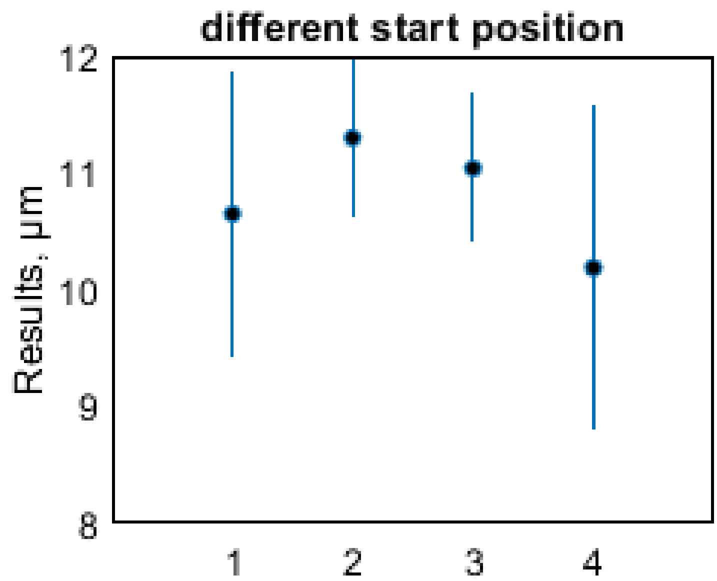


Figure 10. Error bar for results by both test patterns; 1: A, 2: B, 3: C and 4: D

4.2. Least square and minimum zone

The flatness measurements of surface plate calibration are analyzed by two mathematical algorithms; least square and minimum zone. The difference in flatness deviation in each Method by both algorithms is presented in table 11. This difference should be considered when any of these algorithms is used.

Table 11. Percentage difference in flatness deviation in each test pattern by both algorithms

Minimum Zone / least square	Difference, %	
	Unionjack	XY-Grid
	8.4	3.9

5. Conclusions

This study presents flatness measurements for grade 1 granite surface plates using two different test patterns: Union-Jack and XY-Grid. Although the measurement results by both test patterns are consistent, the calibration of surface plates by the xy-grid test pattern increases the number of measured points, lines, and regions by up to 30%, 50%, and 125%, respectively. This gives a more real representation of the flatness value of the surface plate. The surface plate is calibrated four times by each test pattern, where the start position (corner of the surface plate) is changed each time. It is initially expected that flatness deviation should not be affected by changing the start position for the surface plate in each calibration, but the experimental results show a percentage difference in flatness deviation of about 2–10% from one position to another. This difference should be included in the evaluation of the associated uncertainty. The results for flatness measurements of surface plates are analyzed by two mathematical algorithms: least squares and minimum zones. There is a difference in flatness deviation by both algorithms: about 8% and 4% for test patterns union-jack and xy-grid, respectively. This difference should be considered when any of these algorithms are used.

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