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Recommendations for Acceptance Protocol for Flatness of Surface Plates

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Abstract. Assessment and calibration of surface plates becomes necessary demand in production metrology. Surface plates are considered as reference planes for many types of dimensional measurements. There are different measuring instruments that can be used in calibration of surface plates i.e. laser interferometer systems and autocollimator systems. In both measuring instruments, a carriage with foot spacer that carries the reflector/reflecting mirror are used. The problems in calibration of surface plates appear in determination of related effected parameters i.e. plate working size, distance between the two feet of foot spacer and number of tested points over the plate. The determination of these parameters can act as an acceptance criteria or protocol of surface plates. In this paper, a grade 1 granite surface plate is calibrated by a laser interferometer system. Three foot spacers with different foot distance 2, 4 and 6 inches are used. The plate calibration is performed at different working sizes 90%, 80% and 70% of actual plate size. The flatness measurements in these 6 calibrations are analyzed. The results and evaluated uncertainties are evaluated and compared.

Keywords. Surface plates; Flatness measurements; Laser interferometer; Foot spacer; Plate working size.

1. Introduction

Surface plates are considered strong pillars in production metrology [1]. Calibration of check masters; height gauges and heights measurements of industrial products are clear examples for the importance of these plates. They are used as reference planes for such measurement's types [2]. There are various material types of plates; granite, steel and cast iron. The sizes for plates range from few millimeters up to several meters [3]. There are two issues for using of plates; levelling and surface flatness. The plate level can be adjusting by using a high precise digital or spirit level.

The flatness of surface plate is independent feature where the flatness deviation of upper surface of the plate is measured through specified calibration schemes. The flatness of surface plate is defined in many standards as the minimum distance between two parallel planes so that all data points of surface are between the two planes [4, 5]. There are different precise instruments that can be used for the calibration of surface plates [6].

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One of the most accurate instruments is laser interferometer system that can measure flatness deviation with accuracy upto 0.01 arcs [7, 8]. This system depends on the reflected laser beams from a moving retroreflector placed on a foot spacer. The common calibration scheme for surface plates is the Union-Jack pattern. In this pattern, a specified plate working size as a percentage of the surface plate is mapped into eight lines (generators) as a rectangular shape. Each line is divided into several points depends on the used foot spacer. Then the straightness measurements for the whole lines are analyzed to determine flatness deviation of the surface plate [9]. In this paper, the calibration of surface plates is determined to be planned in its optimum design. Two parameters are considered for study; different foot spacers and different working sizes. The plate calibration is carried out at three different foot spacers, 2 inch, 4 inch and 6 inch. The plate is calibrated once more at three plate working sizes, 90%, 80% and 70%. The associated uncertainties in each measurement type are determined [10].

2. Methods and Procedures

In this paper, an instrument of laser interferometer system of 0.01 arcs resolution is used. This system is used for the calibration of a grade 1 granite surface plate. The plate has a surface size of 750 mm × 1000 mm. Three foot spacers of foot distances 2, 4, and 6 inches are used. Three plate working sizes, 90%, 80%, and 70% are considered. In each scheme, the considered working size relative to the plate's actual size is changed.

2.1. Laser Interferometer System

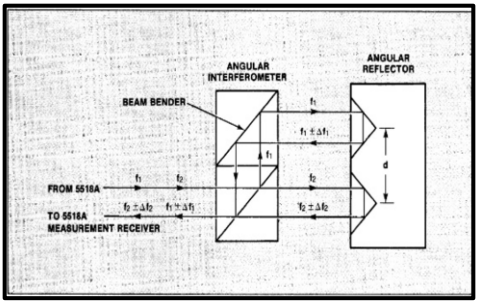

Figure 1. Angular Measurements by laser interferometer system

The laser interferometer works based on principle of displacement measurements using optical interference [10]. A laser beam with two frequencies f1 & f2 is splitted into two; one beam (f1) is moving arm "moveable cube corner reflector" and the other (f2) is fixed arm "fixed cube corner reflector". For angle and flatness measurements, both beam splitter and reflectors optics have different design shape, figure 1. The emitted laser beam from the laser head is splitted into two beams one in the same direction (f2) and the other (f1) moves perpendicular to a beam bender which redirected f1 in a parallel direction to f2. Then, both parallel beams f1 & f2 move towards the other new optical element of "Angular Reflector" which contains two retro reflectors. The beams of f1 & f2 are reflected by f1±Δf1 and f2±Δf2. The difference between them represents the tilt angle of the object that carries the angular reflector.

2.2. Foot Spacer

The foot spacer is a carriage that carries the angular reflector, figure 2. Three foot spacers of different foot separation distances are used. The foot separation distance is identified as the distance between the centers of aligned feet, figure 3. The number of measured points in each line depends on the foot spacer that used. For plate working size of 24 inch × 32 inch, the number of measured points for long side (32 inch) is 16, 8 and 6 points for foot spacers 2, 4 and 6 inches respectively. For short side (24 inch), the number of measured points is 12, 6 and 4 points for foot spacers 2, 4 and 6 inches respectively.

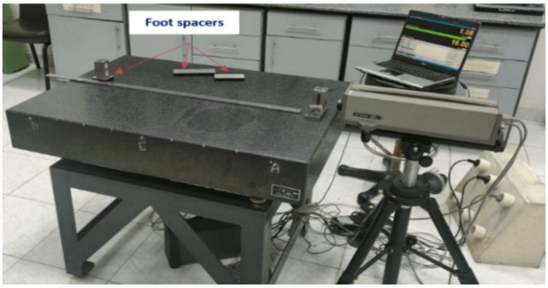

Figure 2. Surface Plate Calibration Using laser interferometer system (foot spacers are indicated)

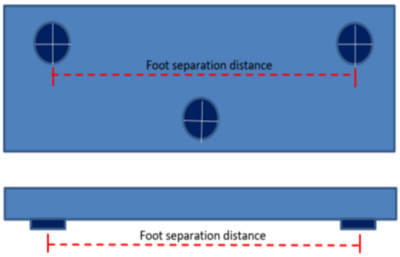

Figure 3. Foot Spacer (Elevation and Side view)

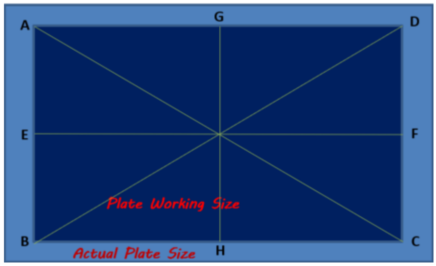

Figure 4. Plate Working Size (in comparison to actual plate size)

2.3. Plate Working Sizes

Each surface plate has an actual size for its upper surface. This actual size is expressed in terms of length multiplied by width of plate upper surface. In practical calibration of surface plate, a border from each side is left. The resulted size for calibration is named as plate working size, figure 4. For plate size 750 mm × 1000 mm, proposed border 100 mm from each end of long sides and 75 mm from each end of short sides. The plate working size is 600 mm × 800 mm.

2.4. Union-Jack Method

In order to calibrate the granite plate, the surface should be mapped to certain number of straight lines, figure 5. One of the most common method in mapping the surface plates is the Union-Jack test pattern. In this method, the plate working size is mapped to eight lines (generators), three parallel to long side, three parallel to short side and two diagonals of the plate. Each line is then divided to equal steps depends on the foot spacer that is used. There are guide arrows for straightness measurement of each line. The straightness deviation of each generator is measured through measuring heights differences at each point on each generator. From the whole straightness of all lines, the flatness deviation of surface plate is determined.

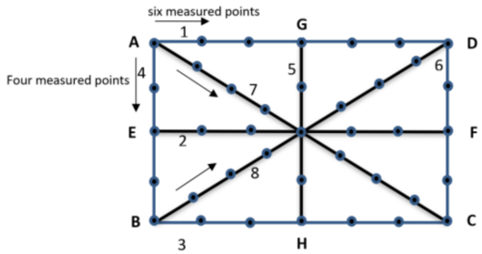

Figure 5. Union Jack Test Pattern for granite surface plate (24×36 inch), foot spacer 6 inch.

2.5. Measurement Procedure

The determination method of flatness deviations for calibrated surface plate depends on measuring instruments that is used. For laser interferometer system, the method for flatness deviations of measured points is based on inclination method. The angular variations at points is measured which are turned into heights. The angular reflector is placed with a guide ruler on a carriage with two contact flat feet, with a certain separation distance. The laser head is placed on a tripod and aligned to angular interferometer and angular reflector. At the beginning in measuring straightness of each line, the interferometer is kept constant while the reflector is moved with equal steps (points) along the measured line and record the reading at each point, figure 6. The carriage is moved to next step to indicate angular variations in comparison to the first position. By the same method, angular variations at test points of the measured line can be measured and the same for all measured lines. The heights (h) at measured points are determined by multiplying the angular variations (θ) to feet step of the carriage (L = 2 or 4 or 6 inches). All measured points are fitted to a reference plane and analyzed to calculate flatness deviation of the measured plate.

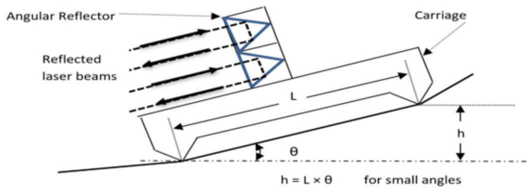

Figure 6. Angular variation of carriage at measured point on tested plate.

3. Results

The granite surface plate is calibrated at two different cases; different foot spacers and different plate working sizes. In all cases, the surface plate is calibrated using a laser interferometer system and union jack method.

3.1. Foot Spacers

The granite surface plate is calibrated at three foot spacers; 2, 4 and 6 inches. The determined working size is ~ 24 × 32 inches. The measurement results are presented in table 1 and figure 7.

Table 1. Calibration of granite surface plate using three different foot spacers

Foot spacer	Out of flatness, µm
	Analyzed by Moody Method
2 inch	15.391
4 inch	11.905
6 inch	14.234

3.2. Plate Working Sizes

The plate is calibrated at different working sizes of 70%, 80% and 90% of the plate actual size. The actual size of surface plate is 750 mm × 1000 mm. The calibration is performed in each case using 2 inch foot spacer. The measurement results are presented in table 2 and figure 8.

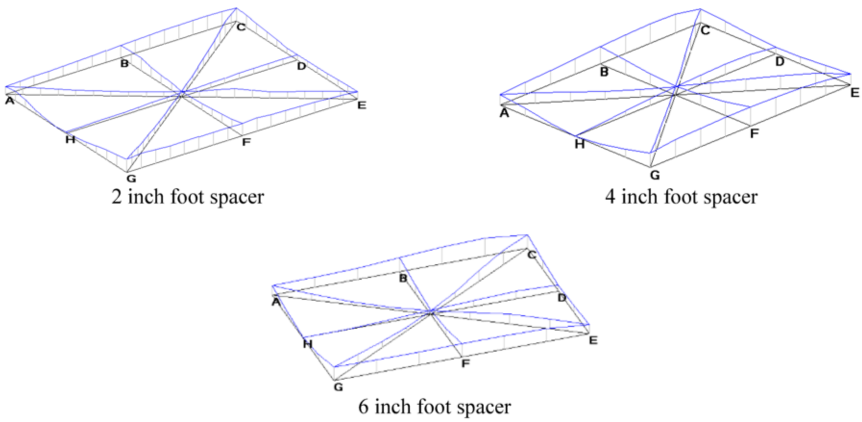

Figure 7. Isometric Plots for Surface Plate Calibration Using different foot spacers

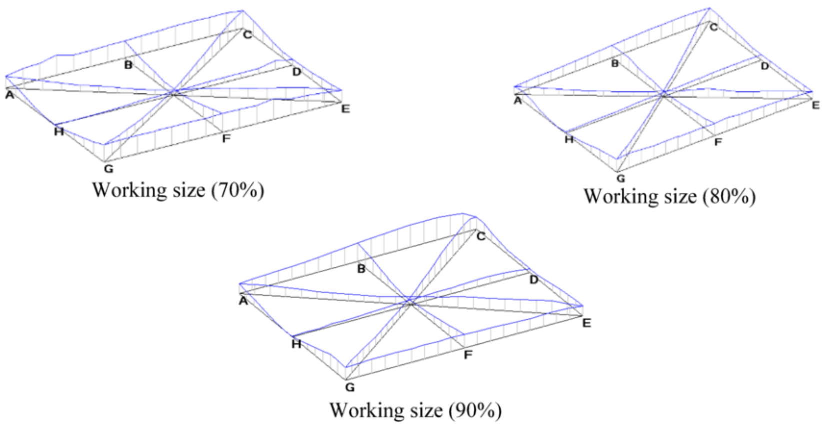

Figure 8. Isometric Plots for Surface Plate Calibration @ different plate working size

Table 2. Calibration of granite surface plate using three different working sizes

Plate working size, % (percentage of plate actual size)	Out of flatness, µm Analyzed by Moody Method
70	9.4471
80	15.391
90	15.573

3.3. Uncertainty Evaluation

The combined uncertainties in surface plate calibrations at each case are evaluated based on GUM [5]. The type A of uncertainty evaluation (random source) depends on the measurement's repeatability in calibration processes of surface plate. For type B of uncertainty (the systematic sources) for flatness deviation depends on affecting parameters on plate calibration i.e. foot spacers and number of measured points. The measurement of flatness deviation using laser interferometer system is based on angular variations (θ) which are observed when a carriage with contact feet separated by a distance (L) is stepwise moved over the calibrated surface plate, figure 8. These angular variations (θ) are then transformed to variation in heights by multiplying (θ) by (L).

Referring to [7, 8], major sources of 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. Table 3 represents the uncertainty evaluation 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	$U(\theta_i)$, arcs	Distribution	Standard Uncertainty $u(\theta_i)$, arcs	Sensitivity factor c_i	associated uncertainty, $u^2(\theta_i)$, arcs	Degree of freedom, ν_i
Inst. 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
Mirror flatness	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 [9, 10];

$$u^2(\varphi) = 2\, u^2(\theta)\, (L/2)^2\, [l + m + n] \quad (1)$$

where: l, m, n are the number of steps over the long, short and diagonal generators; L distance between carriage feet and u(θ) uncertainty in angle measurements. The expanded uncertainties of flatness deviation Uφ measurements of the granite surface plate at each calibration case are shown in tables 4 and table 5 respectively.

Table 4. Uncertainty budget in surface plate calibration by different foot spacers

Type of uncertainty	plate calibration @ different foot spacers		
	2 inch	4 inch	6 inch
Type A (standard uncertainty)	$(0.10)^2$	$(0.10)^2$	$(0.10)^2$

Type B (systematic uncertainty)	$(0.48)^2$	$(0.68)^2$	$(0.88)^2$
Combined standard uncertainty $u_c(\varphi)$	0.49 µm	0.68 µm	0.88 µm
Expanded uncertainty, $U_\varphi = 2\ u_c(\varphi)$	0.98 µm	1.37 µm	1.77 µm
Effective degree of freedom, ν_{eff}	∞	∞	∞

Table 5. Uncertainty budget in surface plate calibration by different plate working sizes

Type of uncertainty	**plate calibration @ different plate working size**		
	70%	**80%**	**90%**
Type A (standard uncertainty)	$(0.10)^2$	$(0.10)^2$	$(0.10)^2$
Type B (systematic uncertainty)	$(0.51)^2$	$(0.96)^2$	$(1.34)^2$
Combined standard uncertainty $u_c(\varphi)$	0.52 µm	0.96 µm	1.34 µm
Expanded uncertainty, $U_\varphi = 2\ u_c(\varphi)$	1.03 µm	1.34 µm	2.69 µm
Effective degree of freedom, ν_{ef}	∞	∞	∞

4. Discussion

4.1. Foot Spacers

The results and associated uncertainties are presented in table 6 and figure 9. The number of measured lines and points in each type are presented in table 7. The calibration of surface plate by different foot spacers resulted in different measured values of plate flatness errors. As shown in table 6 and figure 9, the plate flatness errors for calibration by 2 inches foot spacer are higher in value in comparison to the plate calibrations by 4 inches and 6 inches foot spacers. These results for calibration by 2 inch foot spacer may be normal or expected. The number of measured points all over the plate as in table 7 and figure 10 can interpret this conclusion. As the number of collected measured points during the calibration is increased, the flatness errors are raised and introduce real representation for the surface of calibrated plate. The unexpected results are found for the plate calibration by 6 inch foot spacer. The number of measured points is decreased to be about 38% of that for calibration by 2 inch foot spacer. This low number of measured points are expected to be reflected on the results of plate flatness errors.

The results of flatness errors for plate calibration by 4 inch foot spacer come in consistency with the stated flatness errors of grade 1 surface plate with size 1 m × 1 m. For the evaluation of associated uncertainties, the uncertainty in plate calibration by 2 inch foot spacer is low (high accuracy) in comparison to that by 4 inch and 6 inch foot spacers. It can be claimed that the plate calibration by 2 inch foot spacer is suited for plates of small surface sizes lower that 1 m, 4 inch foot spacer is suited for plates of medium surface sizes upto 2 or 3 m and 6 inch foot spacer is suited for plates of large surface sizes.

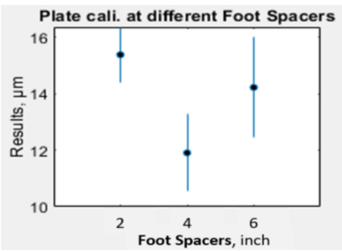

Figure 9. Error bar at different foot spacers

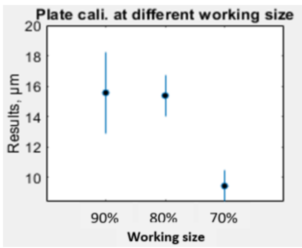

Figure 10. Error bar at different working sizes

Table 6. Calibration of granite Surface Plate at different Foot Spacers

Foot Spacer	Out of flatness, µm	Expanded uncertainty (U), µm
2 inch	15.39	0.98
4 inch	11.91	1.37
6 inch	14.23	1.77

Table 7. Number of measured points at different Foot Spacers

Foot Spacer	Measured lines	Measured points all over the plate
2 inch	**8**	**128**
4 inch	**8**	**64**
6 inch	**8**	**48**

4.2. Plate Working Sizes

Results and associated uncertainties are presented in table 8 and figure 10. Number of measured lines and points in each type are presented in table 9.

Table 8. Calibration of granite Surface Plate at different working sizes

Working size (as percentage of plate surface size)	Out of flatness, µm	Expanded uncertainty (U), µm
90%	15.57	2.69
80%	15.39	1.34
70%	9.45	1.03

Table 9. Number of measured points at different working sizes

Working size (as percentage of plate surface size)	Number of measured lines	Measured points all over the plate
90%	**8**	144
80%	**8**	128
70%	**8**	112

As shown in table 8, the plate flatness errors for calibration at 90% working size are higher in value in comparison to the plate calibrations at 80% and 70% plate working sizes. These results for calibration at 90% working size may be expected as the working size includes a part of the border area of surface plate. The number of measured points all over the plate as in table 9 can illustrate this conclusion. As the number of collected measured points during the calibration are increased, the flatness errors are raised for the surface of tested plate. The unexpected results are found for the plate calibration at 70% working size. The number of measured points is decreased to be about 78% of that for calibration at 90% working size. This low number of measured points are expected to be proportionality reflected on the results of plate flatness errors. The low value of flatness errors for plate calibration at 70% working size can be interpreted in a way that the decreasing of working size especially towards the middle area of the plate, resulted in calibration of unusable area of the plate. The surface plate is commonly used in this narrow area over 70% and less than 90% of the plate surface size. The results of flatness errors for plate calibration at 80% working size are almost the same results for calibration at 90% working size.

For the evaluation of associated uncertainties, the uncertainty in plate calibration at 90% working size is so high (low accuracy) in comparison to that for calibration at 80% and 70% working size. The associated uncertainties for plate calibration at 80% and 70% working size have no big differences. It is commonly advised to calibrate large and medium-sized surface plates at 80% working size. For small sizes surface plates, it is recommended to be calibrated at the whole surface area.

5. Conclusions

The calibration of 1 granite surface plate has carried out at two different considered cases; different foot spacers and different plate working sizes. The flatness errors for calibration by 2 inches foot spacer are higher in value in comparison to the plate calibration by 4 inches and 6 inches foot spacers. It can be claimed that the plate calibration by 2-inch foot spacer is suited for plates of small surface sizes lower than 1 m, 4 inch foot spacer is suited for plates of medium surface sizes upto 2 or 3 m and 6 inch foot spacer is suited for plates of large surface sizes. The plate flatness errors for calibration at 90% working size are higher in value in comparison to the plate calibrations at 80% and 70% plate working sizes. These results for calibration at 90% working size may be expected as the working size includes a part of the border area of surface plate. The study presents inconsistent results among all cases, so it is advised for suppliers and customers to agree about the acceptance protocol for flatness of surface plate. This protocol shall determine the tested area and number of tested points for assessment of the surface plate.

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