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Measurement Uncertainty in Calibration of Measurement Surface Plates Flatness

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A flat measurement surface e.g. a measurement plate, can be considered as the origin for performing most form and position measurements on measured objects. In order to use measurement plates in a proper way, it has to be assured that they are really flat and suitable for measurements. Flatness of measurement surface is determined indirectly by measuring the straightness of individual lines that build up the measurement grid. These lines are further divided into measurement steps that suit the dimensions of measuring instruments. Straightness of a measurement line is calculated for each line separately by measuring inclination of each measurement position, whereas flatness deviation of the entire surface is determined by linking the results of separate lines.

Backgrounds, procedures and measuring equipment for performing such measurement are well known, whilst the uncertainty of measurement surface calibration remains undetermined. Without properly expressed uncertainty, a measurement means all but nothing. Therefore, a determination of measurement uncertainty has to be assured.

This paper presented a new approach towards determining measurement uncertainty of flatness measurement, based on the Monte Carlo method. A complete measurement system is dissected into separate components, their amplitude and influence is evaluated, whilst measurements are simulated. Furthermore, an impact of grid parameters (size, density, number of measurement steps) on measurement result is evaluated as well.

Keywords: production measurements, length measurements, measuring uncertainty, calibration, flatness measurement

0 INTRODUCTION

Flatness of surfaces can be established by different flatness measurement methods. The most common means for performing such measurements are electronic levels, laser interferometers and autocollimators. When using an electronic level to perform a surface measurement, a measuring instrument itself is moved over the measured surface, using lines of the measurement grid as guidelines to be followed. The measurement grid is composed of individual lines, and straightness is measured for each of these lines. In order to determine the flatness of the measurement surface, straightness measurements results of individual lines are arranged and combined into a value, which represents the level of flatness deviation. Each measurement surface is ranked according to the flatness level, and adequacy of these planes is determined by regular calibrations. Such measurements are influenced by many factors, which directly and indirectly influence the results and their reliability.

There are many ways to determine the measurement errors which affect the measuring uncertainty. A thorough knowledge of all impact factors that affect the measurement and its result is always a good starting point. The way in which data is scattered can also be established by determining these impact factors. By employing simulations, measurements are automated, whilst the input data changes in the range of pre-determined boundaries. [1]

All characteristics of each and every element of a measurement system, that are the part of the measurement, are simulated – we attempt to take into account all important factors that affect the measurement:

- measurement plate (mechanical properties, damages…),
- measurement equipment,
- surroundings (temperature, vibrations, dirt, dust…) and

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- person performing the measurement (carelessness, positioning errors…). [2]

The more factors are taken into account and the more precise they are, the more accurate the results will be.

1 SIMULATIONS OF FLATNESS MEASUREMENT

For each specific measurement system, separate impact factors are determined and their boundary values entered into simulation. Besides the already mentioned impact factors, which influence the measurement results and their uncertainty on a larger scale (measurement plate, measurement equipment, influence of surroundings and person, performing the measurement), there is a lot of less important factors with smaller influence, which can usually be prevented, but only if the suitability of equipment is assured and if their negligibility is confirmed. Such factors are the quality of the signal, adequacy of the cables and connectors, suitability of the batteries or deviation of results caused by transversal declination of the measurement device etc. In this way identical conditions for virtual measurements which cannot always be 100% assured for real-world measurements, are ensured. [3] and [4]

Fig. 1 shows the algorithm of a simplified simulation model which was used in order to determine measurement uncertainty. The results of such a simulation are all important values:

- flatness of the surface,
- measurement uncertainty,
- upper and lower boundary of results scatter,
- height coordinates of individual points that are part of the measurement grid.

Besides basic surface geometry data and measurement grid data (length and number of measurement steps along the measurement line), all important factors that affect results and their uncertainty are entered into simulation. The number of iterations (repetitions of simulation cycle) must be defined as well. The results of simulations featuring more iterations will be more precise, but the time needed to carry out the simulation will be prolonged accordingly. So a compromise to choose the smallest value for iterations that ensures satisfactory results, is needed. [5] and [6].

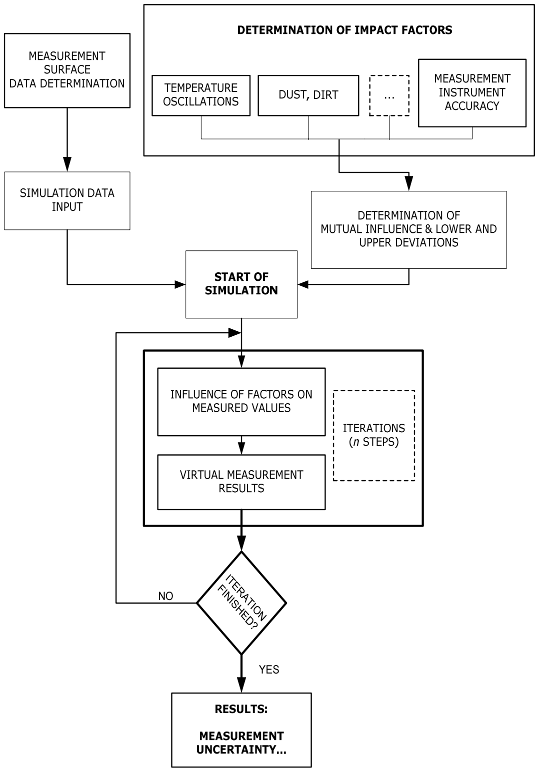

Fig. 1. *Algorithm of a simulation model*

2 DEFINITION OF IMPACT FACTORS AND THEIR INFLUENCE

Errors that occur during flatness measurement are the consequence of the person who performs the measurement, influences of measurement equipment, surroundings and other impact factors. Each and every measurement device is a source of its own errors that depend on design, construction, wear as well as other factors. At the same time, the whole measurement system is exposed to surroundings and its factors (deviations of temperature, humidity, vibrations…) and to the level of experience of the personnel performing the measurement. All these factors influence the results. [7] and [8]

The basic element of the discussed approach regarding the topics of measurement uncertainty is that it is possible to determine all the impact factors that affect the measurement and its result even before the measurement itself is carried out. It is important to determine individual factors and evaluate their influence. Common contribution of all the impact factors can be represented with the following equation [9] and [10]:

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

2.1 Contribution of Measurement Equipment to Measurement Uncertainty

Reliability of the used measurement equipment is one of the main factors that affect the reliability of the measurement and its results. In order to determine the uncertainty of the measurement, the measurement range has to be considered as well. Because the characteristics of the measurement device changes throughout the measurement range, it has to be calibrated accordingly. Electronic levels are calibrated using a sine bar [11].

The largest deviations are 0.5 µm/m (point 13) and -0.4 µm/m (point 4). Both values are more or less equal, so this is the largest deviation. As 4.8484 µm/m corresponds to 1 arc second, the established deviation of 0.5 µm/m corresponds approximately to 0.1 arc second. Thus, the uncertainty component in this case is the result of the uncertainty of calibration of measurement device, and comes to $F_{MN} = \pm 0.1''$.

2.2 Temperature Deviations and their Influence on Flatness of Surface

Besides the measurement system characteristic, temperature is a factor, which affects the result and the measurement uncertainty the most. Even the smallest changes of temperature gradient between the upper and lower plane of measurement plate have a large impact on its flatness. To define the contribution of these temperature dependant oscillations to overall measurement uncertainty, we need to determine how the temperature gradient changes over time. Measurements are performed over a longer period, using very accurate temperature measurement equipment.

The largest temperature difference between both planes is $\Delta T_{max} = 0.188$ K, whilst the smallest comes to $\Delta T_{min} = 0.159$ K.

From that, a change of measurement plate flatness can be calculated.

$$\Delta T_{negot} = \Delta T_{max} - \Delta T_{min} = = 0.0285\ °C \quad (2)$$

To determine how the plate is curved, the following formula is used:

$$X = \frac{D_T \cdot a \cdot L^2}{8 \cdot B} = \frac{0.0285 \cdot 5.6 \cdot 10^{-6} \cdot 2.295^2}{8 \cdot 0.22} = 0.48\ \mu m \quad (3)$$

In equation, B is plate thickness (m), D_T is temperature deviation between upper and lower plane of meas. plate (K), a is the material extension coefficient ($5.6 \cdot 10^{-6}$ K^{-1} for granite) and L is the handled plate length (m).

The data (plate dimensions) are entered into the formula and the result is converted into arc seconds. Thus, the diagonal deviation is $F_{TD} = \pm 0.0214''$ for a single measuring step. Adequately, both width and length components can be calculated, but in this case, the diagonal component will be used, being the largest.

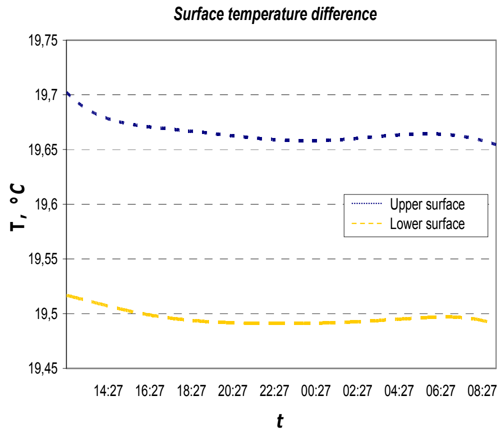

Fig. 2. *Average temperature oscillations of lower and upper measurement plane*

Table 1. *Results of electronic levels calibration*

step	1	2	3	4	5	6	7	8	9	10	11	12	13
slope, µm/m	-40	-20	-16	-12	-8	-4	0	4	8	12	16	20	40
deviation, µm/m	-0.1	0.3	0.4	-0.4	-0.1	0.1	0.0	0.1	0.3	0.2	-0.2	-0.1	0.5

2.3 Influence of Temperature Deviations on the Measurement Equipment

Additional deviations occur because of ambient temperature changes and their influence on the electronic level during measurement. A typical measurement range of electronic levels amounts to ±200 arc seconds. A deviation caused by the temperature change (as declared by the manufacturer) comes to 0.02 % of the measurement range for deviation of 1 °C. This value has to be corrected according to the established actual temperature oscillation, which is 0.7 °C.

$$P_T' = 0.7 \times 0.02\% \cdot 400 = 0.056" \tag{4}$$

After all the data is entered into the upper formula, a surroundings temperature oscillation component can be determined: $F_{NT} = \pm 0.028"$.

2.4 Measurement Equipment Positioning Deviation

A further error of the measured angle is caused by an inaccurate positioning of the measurement electronic level onto its measurement positions. To evaluate this error, some assumptions will be employed. The first assumption is an average slope difference of 3" between two measurement positions. In case of an angle of 0" for the first measuring position, the angle for the next measuring position would be 3". If the electronic level was misplaced for the whole length of the step, it would show an inclination of 3" instead of 0".

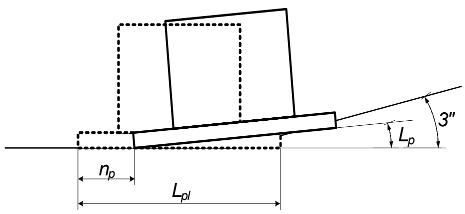

Fig. 3. *Error, caused by inaccurate positioning of the electronic level*

When placing the measurement equipment, some error is always present, so we assume that this error is ±1 mm. When we take the dimensions of the measurement equipment into consideration, we get:

$$L_P = \frac{n_P}{L_{PL}} \cdot 3" = \frac{1}{140} \times 3" \\ L_P = 0.021" \tag{5}$$

L_P is inclination deviation (arcsec), n_P is positioning error (mm) and L_{PL} is base length of the electronic level (also mm).

The component of uncertainty because of inaccurate positioning of electronic level to measuring position is $F_P = \pm 0.021"$.

2.5 Vibration Caused Deviations

Vibrations are certainly amongst factors that can affect measurement results and measurement uncertainty on a larger scale. By using electronic levels as a means for performing measurements instead of e.g. laser interferometer or autocollimator, it is possible to eliminate a significant part of vibrations. The main advantage of using electronic levels for inclination measurements is the possibility of ‘differential measurement’, using two units simultaneously. This configuration has proven itself as a very useful setup, which can successfully eliminate the influence of vibrations on measurement results.

Both electronic levels placed on a measurement plate are oriented in the same way, so the vibration influence is practically the same on both units. The results of such measurements are only the difference of actual inclination between the units. A practical test based on generated disturbances has shown positive results of this configuration.

There are of course exceptions when the vibration impact can be of importance. This is mostly the case when we deal with structural defects or shape deviations, such as varying plate thickness. There, high frequency localized vibration modes for plates of slowly varying thickness occur within the vicinity of maximal or minimal cross-sections. [12] Such influence is possible when vibrations are constantly present during measurement process. Usually, this is not the case, especially under laboratory conditions, where the measurement plates are in most cases placed onto an appropriate foundation, apart from vibration sources. This is also the reason why the vibrations as the possible influence for measurement result fluctuations have been neglected.

2.6 Impact of Dust on Measurement Surface

The determination of the uncertainty component caused by dust and dirt, which can be found on the measurement plate, is by far the toughest. An analysis of size, number and type of dust particles that are located on the surface and in the air around the measurement place, would be vast. Since before and during each measurement the measuring surface is thoroughly cleaned, some larger impurities are removed. Also, impurities are not allocated equally over the entire area, so their impact on the measurement is limited on individual measuring positions only. It affects only the results on some positions, not all. Regardless, let us assume that the contribution of dust and impurities to the total uncertainty is approximately $F_N = \pm 0.01''$, which is taken into consideration in the simulation.

According to formula (1), the total influence of all the handled components is:

$F_{TOT} = 0.181''$.

3 SIMULATION RESULTS

As the number of iterations greatly affects the reliability of the results, the relation between result values and numbers of iterations has to be examined.

Fig. 4 shows that the results are scattered to a large extent when using a small number of iterations (for example 100 and 1000), yet the results become increasingly uniform by increasing the number of iterations, resulting in a more stable simulation system.

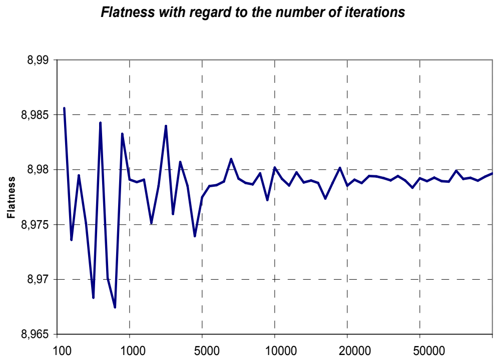

Fig. 4. *Flatness as result of simulation according to the number of performed iterations*

The oscillation of results reduces with an increase in iterations. This tendency is shown on a much smaller scale than before, as the evaluations represent the lower and upper limits of the process. The span of results (i.e. by simulation covered area) is increased, for a larger number of iterations it means a better coverage factor of the model, therefore the model reaches more extreme values.

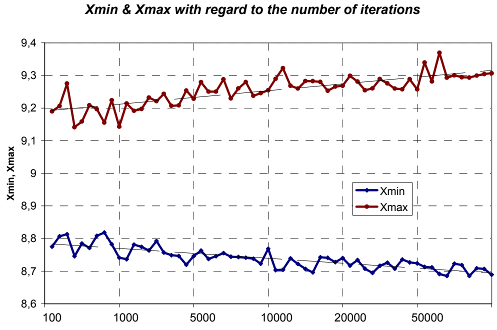

Fig. 5. *Upper and lower limit of flatness with regard to the number of iterations*

The span is shown as the result between maximal and minimal value of flatness, obtained as the result of simulations. The area, covered by the simulation, as well as the span of the results is increasing according to the number of iterations.

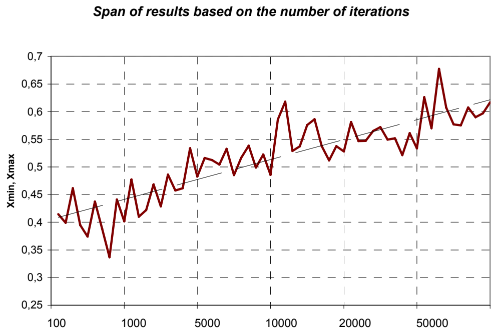

Fig. 6. *Span of results - difference between largest and smallest value*

On the lower graph it is shown that the oscillation of results is higher when the number of iterations is small, and by increasing the number of iterations the oscillation of results is increasingly reduced. The average value of results stays almost unchanged independent of the number of iterations.

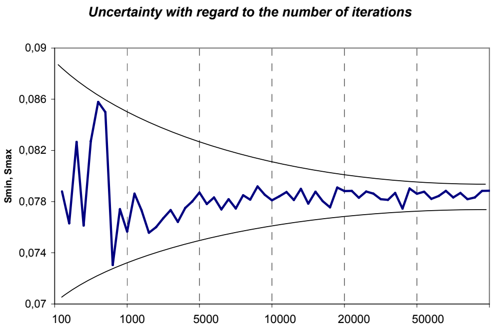

Fig. 7. *Oscillation of results according to the number of iterations*

The results of simulations as well as the results of actual measurements show that the uncertainty of the measurement changes according to the coarseness of the measurement grid. When a coarse grid with fewer but longer measurement steps is used, the uncertainty is greater than when using a grid which has more steps that are shorter.

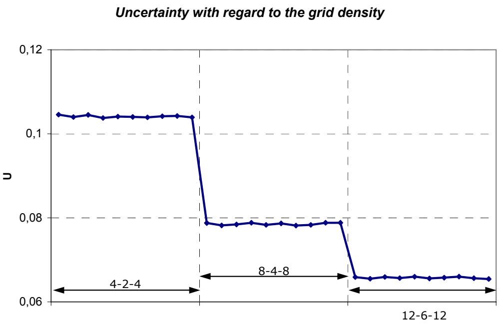

Fig. 8. *Influence of grid density on measurement uncertaint.*

4 CONCLUSION

It was shown that the Monte Carlo based simulations are very suitable for analysing measurement systems or for carrying out virtual flatness measurements. Even the results of a simplified model correspond very well to the results of actually performed real-world measurements. Therefore, with a detailed analysis of individual factors and with a more precise definition of them and their influence on the measured values, it would be plausible to anticipate even more accurate results.

Another important finding is, that the measurement grid has do be adapted to the size of measured surface, yet there is no need to take the shape of it into account. Uncertainty can be vastly improved by increasing the number of individual measurement steps and by reducing their length, yet even here there is no need for exaggeration. Nevertheless, the dimension of the measurement equipment represents a limit of its own. Another such limit is the time that is available to perform the measurement. As the goal of presented simulations is to simulate real-world measurements, actual limits must also be taken into consideration.

In order to achieve satisfactory results, at least 10.000 iterations have to be carried out. Using less iterations, the oscillation of the results and their uncertainty is much too high to be trusted. Such fast simulations are adequate only when a fast examination and evaluation of the simulation results is needed and when a simulation will be further optimised. It is possible to somewhat improve the reliability by increasing the number of simulations, but on account of time needed to carry out the simulation. Considering the constant increase of raw processor power, this can soon be neglected, as it will be possible to run the simulation with 50.000 (or more) iterations instead of 10.000 that are currently used.

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