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CALIBRATION OF CAPACITIVE SENSORS AND ELECTRONIC LEVELS FOR THE STRAIGHTNESS MEASUREMENTS USING MULTIPROBE METHOD

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Résumé

L'objectif est de mesurer une rectitude sur une longueur de 300mm avec une incertitude nanométrique. La méthodologie proposée correspond à un processus dit de mesure par propagation. L'utilisation de l'hypothèse des petits déplacements conduit à la résolution d'un système linéaire surdéterminé. Le second membre de ce système est composé d'informations provenant des capteurs capacitifs et des niveaux électroniques.

Le calcul d'une solution optimale au sens des moindres carrés nécessite de prendre en compte les incertitudes nécessairement différentes des deux types de capteurs ce qui conduit à une méthode de moindres carrés généralisés. La première opération consiste à étalonner les capteurs et à évaluer l'effet sur les rectitudes calculées.

Abstract

In this work, the straightness length 300 mm measurement under nanometer uncertainty. The proposed methodology represents a process known as propagation using the assumption of small displacement which leads to solving an overdetermined linear system. The experimental studies were carried out on the capacitive sensors and electronic levels.

The least squares mathematic method is apply to calculate the optimal solution. This method requires taking into account the uncertainties of the two different types of sensors leads to method of weighted least squares. The first step is to calibrate the sensors and to estimate the effect on the calculated straightness.

Introduction

The Laboratoire National de Métrologie et d'Essais (LNE) has developed an innovative ultra precision coordinate measuring machine traceable to the national length standard [1]. The position along z direction were measured using four capacitive sensors. These sensors target diameter 300 mm flat surface cylinders used as flatness references.

To measure the shape of those aluminum references with nanometric uncertainties, scanning system is only solution for requirement.

In general, the sensors was located in the scan direction, the scanning systems consisting of two [2], three [3] and four [4] distance sensors have been proposed. Recently, multiple distance sensor systems [5] are realized the multi-ball cantilever and white light interferometer as coupled distance sensors and angular information is provided by an autocollimator.

In this paper, a sensor system of four distance sensors has been proposed in order to the high-accuracy topography reconstruction. The electronic levels have been introduced as angular scanning stage measurement. The measuring propagation on straightness also approach to validated due to it can be implement the same technology as those sensors are used on this machine.

Principle of propagation

The measurement principle is based on a propagation process using the scanning stage displaces along the artifact [6]. At each scanning step, the new unknowns and equations are introduced. In additions, the redundancy rapidly increases compared to the number of sensors. The higher redundancy of information can be reducing the uncertainty of measurement (at least by averaging effect) and provided a "self-calibration" form the results or rather highlight the incoherence. Despite that it is difficult to identify the difference between a plane and a sphere via this method without introducing additional information.

This information can be either the relative sensors position or the scanning stage rotation which can be measured using an electronic level or an autocollimator. The utilization of the autocollimator is very interesting in terms of uncertainty in straightness measurement however the passage from the straightness to the flatness requires the knowledge of the relative rotation of the straightness. This method seems to be out of reach for the autocollimator except using a "Union Jack" strategy on flatness marbles but it can be poses the problems.

The experimental bench is equipped with 16 capacitive sensors (4*4 array) due to the plan measurement objective [7]. This research presents straightness from a line of four sensors.

The relative position of four sensors are characterized by two unknowns e_{m2} and e_{m3} . as shown in Figure 1. The system describing the propagation required one or, more generally, a linear combination of these two unknowns to resolved the problem.

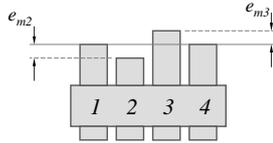


Figure 1 : Convention used to locate the relative position of sensors

The the scanning stage characterization have been chosen by using $e_{m2} + e_{m3}$. In addition, it is very difficult to determine $e_{m2} + e_{m3}$ in order to the uncertainty in the determination or any other linear combination of the two values induces to a highly amplified uncertainty on the profile [2]. Therefore the electronic level was utilize to measure the pitching motion of the matrix scanning stage, which introduces additional information and determines directly the position error from the rotational movement of the scanning stage.

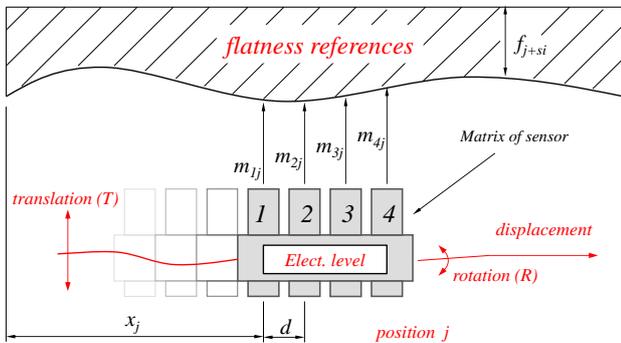


Figure 2 : Straightness measurement using 4 capacitive sensors

In Figure 2, the scanning position x_j is defined as the position from the left edge of the scanning stage. $s_i = i - 1$ is the position of sensor i compared with the first sensor. The positions of the n equidistant sensors are denoted by index $j + s_i$ in range of artifact for each measurement.

For each position of scanning stage, there are defects in guidance of scanning stage: translation error (T_j) and pitching error (R_j).

The measurements at each position of scanning stage are variations of distance of the i th sensor at the j th position from the topography is denoted m_{ij} .

The distance of the sensor m_{ij} is composed of the unknown topography (f_{j+s_i}), the scanning stage error (T_j) and (R_j), and the relative position of sensor (e_{m_i}).

The implementation of the scanning stage is described by the set of equations [8] using following equation (1)

$$m_{ij} = -f_{j+s_i} + T_j + R_j s_i d + e_{m_i} \quad (1)$$

The measured angle (N_j) is the angle of the moving part of the scanning stage in relation to the flatness reference given by the electronic level in each of its positions. The unknown R_0 is introduced, it corresponds to the angular different adjustment setting between the scanning stage and electronic level.

$$N_j = R_0 + R_j \quad (2)$$

$$i = 1, \dots, m \quad (\text{sensor}), \quad j = 1, \dots, n \quad (\text{position})$$

Reconstruction of topography

For each position of the scanning stage corresponds 5 lines in the system. The first 4 equations concern the distance measurements. It is therefore the information type "length". The fifth equation concerns the angular measurement which is the information type "angle."

We propose to solve this system by least-squares method, but the direct solution is not satisfactory because the residuals which must be minimized are different type (lengths and angles).

$$\sum \varepsilon^2 = \underbrace{\sum (\quad)^2}_{\text{Residual type « length »}} + \underbrace{\sum (\quad)^2}_{\text{Residual type « angle »}}$$

Minimization of these equations provide a solution that depends on the choice of units because this choice gives a different relative weight on information from the capacitive sensors compared to those provided by the electronic levels. In the end, the solution is took into account the uncertainties in the method of weighted least squares, but three-way resolution is possible [9].

The two first methods (Figure 3) involve to solve subsystem of the whole problem by focusing either capacitive sensors measurement (method of "sensors preponderant") or electronic level measurement (method of

"levels preponderant"). These two methods are generally extreme case in the weighted least-squares solutions [7].

The third method is to solve the complete system using the weighted least squares method. On simulated data, so in the absence of measurement uncertainties, the three strategies provide obviously the same result. On experimental data, the results are different and the analysis of differences (Figure 4) provides a quality criterion.

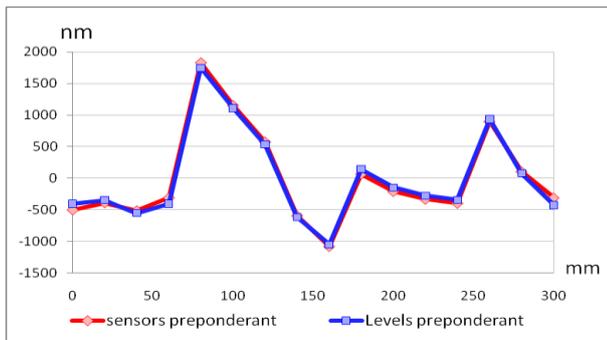


Figure 3 : Calculated profiles by the method « sensors preponderant » and « levels preponderant »

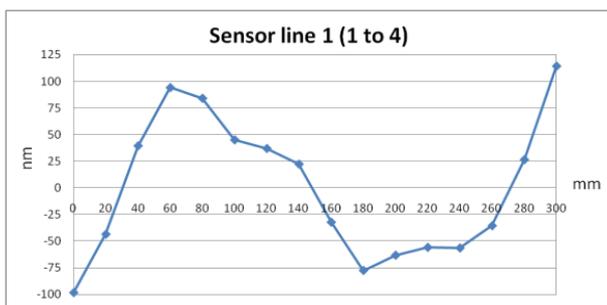


Figure 4 : Incoherence of profile between two methods

Figure 4 shows that the extreme strategies provide the difference of the profile in the order of ± 100 nm. For this curve, the sensors are not calibrated, data from the capacitive sensors is denoted in nanometers and data from electronic levels is denoted in microradians. The incoherence will decrease due to the calibration that we

present below, but remain significantly (Figure 13). We will calculate the final profile with the weighted least squares method which is not presented here.

Experimental bench

Flatness references are calibrated using a scanning process where the information returned by sixteen capacitive sensors arranged in 4x4 matrix is computed [10] (Figure 5). The matrix is put on a flat surface plate and a 300 mm XY stage is used to scan the matrix under the reference flatness. Two inclination sensors are integrated on the experimental bench (Figure 6) : one inside the capacitive sensor matrix and one above the flatness reference.

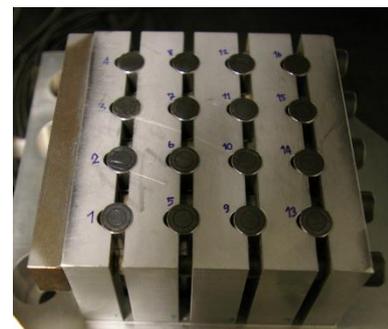


Figure 5: 16 capacitive sensors

The resolution of the inclination sensor is one micro-radian which is not sufficient to be comparable with the resolution of the capacitive sensors. Nevertheless, the repeatability of the inclination sensor is better than its resolution so it is possible to increase the resolution making the sensor oscillate. For that purpose, four piezoelectrics actuators are introduced in the experimental bench, one to rotate the capacitive sensor matrix in which the first inclination sensor is integrated and others three to make oscillate the reference on which the second sensor lies.

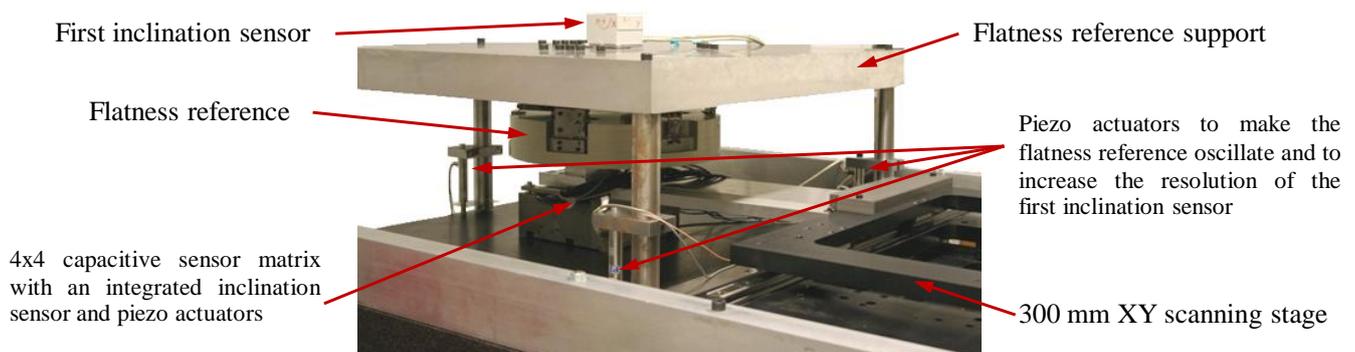


Figure 6: The experimental bench

Calibration of capacitive sensors

The calibration of capacitive sensors should be performed in-situ to avoid uncertainties related to the disassembly of the scanning stage as the deformation under the effect of tightening or orientation relative to the target. Capacitive sensors are calibrated one by one so that they can be placed as the Abbe principle in relation to the laser.

To make successively each capacitive sensor in Abbe principle from the laser required the development of a particular procedure [7].

The bench has a complementary device compared with Figure 6 for supporting instruments (Figure 7):

- Laser, corner cube and cube beam splitter (circled in blue)
- Four extra capacitive sensors measuring the movement of the flatness reference support (circled in red).

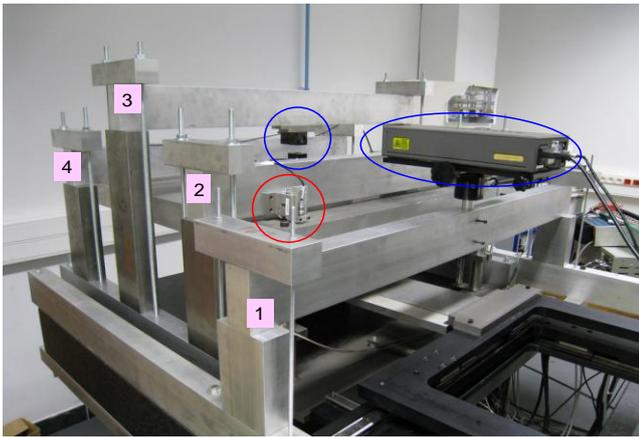


Figure 7 : Bench calibration phase with the interferometer

Displacement required for the calibration phase are created by three piezoelectric actuators that support the flatness reference support to generate a moving plane parallel to the group of sensors (Figure 8).

During this phase, the electronic level indicates no rotation, that is to say that the displacement is parallel better than 1 microradian (resolution of electronic level). We create a study of reproducibility by calibrating the sensor 1, to the sensor 16 respectively then again seven times in a row. As a result, between each calibration of a four-hour, the table moved. This leads to excesses the evaluation in the assessment of uncertainties.

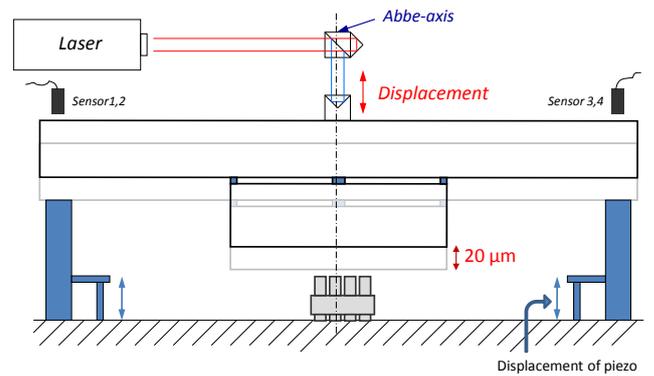


Figure 8: Calibration phase

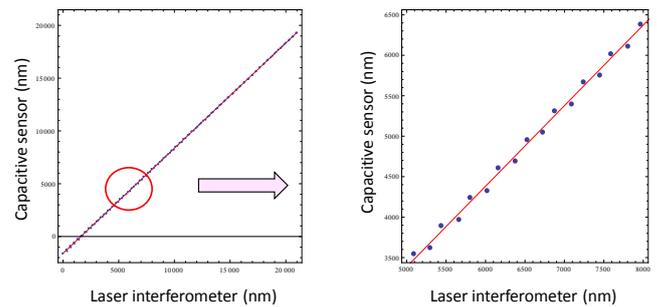


Figure 9: Calibration curve of a capacitive sensor

Figure 9 shows the acquisitions calibration of a capacitive sensor. The general appearance is a straight line identified in the sense of least squares. The passage to a parabolic model or a polynomial of higher degree, reduces the value of the residual which can be tempting. However, the residuals between the least-squares line and measured points are not stable for an acquisition to the other making use of a polynomial of highest degree is illusory.

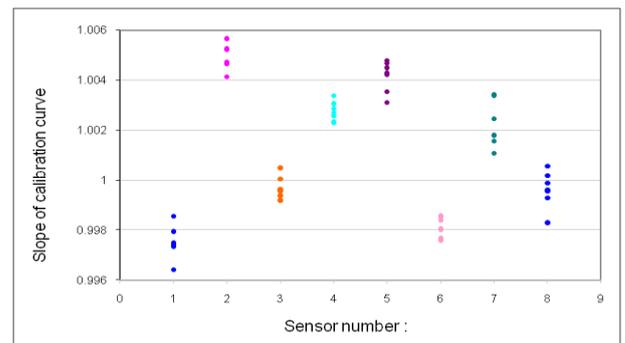


Figure 10: Reproducibility of the calibration slopes

Figure 10, for the eight first sensors, the slopes of calibration curves vary by about $\pm 0.5\%$. If the first cycle of measurements is excluded, the reproducibility of the slope of each sensor is about ± 1 in 1000. As the sensors are used on a race of about $20\mu\text{m}$, this represents $\pm 2\text{nm}$. This validates the stability of the sensor response time.

Calibration of electronic levels

It is necessary to calibrate electronic level « in-situ ». The difficulty of path and implementation of reference angular which is better standard than the level (ex. autocollimator), led us to have recourse to the measurement of angles by variations in length.

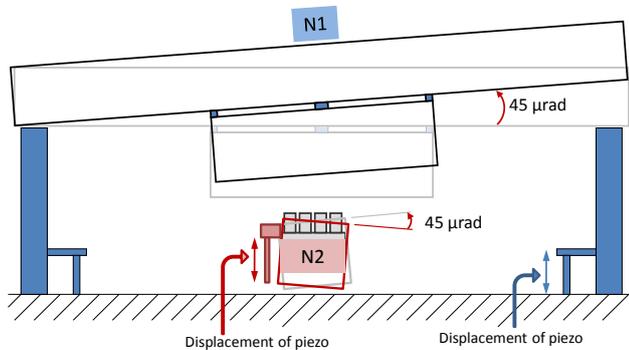


Figure 11 : Calibration phase

To realize the calibration of electronic level, we studied two strategies related to different sources of information.

- The displacement indicated by the laser and the four additional capacitive sensors placed at each corner of the support of the reference plane. In this case, the idea is to drive the piezoelectric actuators to define a rotation axis passing through two capacitive sensors acting as zero detector. This method can use to calibrate only the level of the support part.
- The displacement come from the 16 capacitive sensors in scanning stage. The idea is to calculate a plan in the sense of least squares according to the indications of the 16 sensors. This method is used to calibrate the two electronic levels.

We chose to calibrate our levels with 16 capacitive sensors having shown that this method has uncertainties smaller than the first [7], especially it also has the advantage of treating the same way for the two levels.

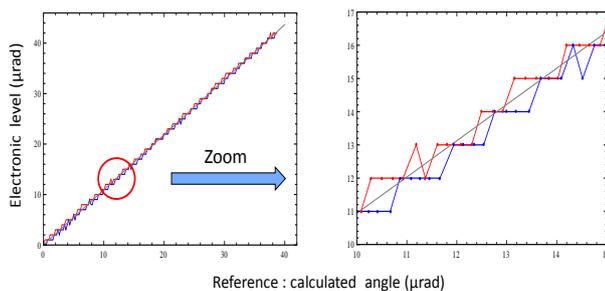


Figure 12: Calibration curve of an electronic level

Figure 12 shows the electronic level measurements in comparison to the calculated angle using 16 sensors as a reference. The blue dots represent the measurements of the level in up part of the piezoelectric actuator, and those in red correspond to the down part. The results led them to choose a simple linear correction.

Contribution of calibration of capacitive sensors

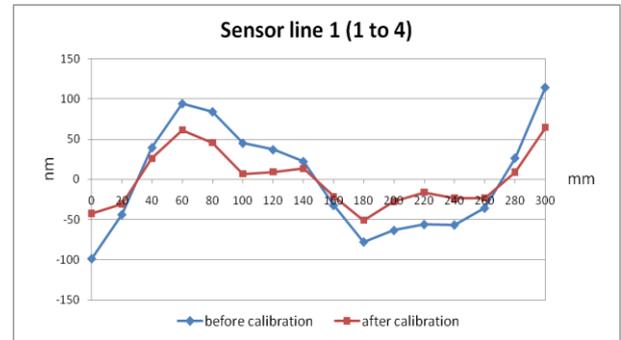


Figure 13 : Difference between two calculated method

The blue curve (Figure 13) is the difference of each point of the profile between the two extreme strategies of calculation before the calibration of sensors, it has already been shown in Figure 4. The red curve takes into account the calibration of capacitive sensors. We find a division of incoherence about a factor two.

Contribution of calibration of electronic levels

The difference between the profiles obtained using the method of "sensors preponderant" and "levels preponderant" before and after calibration of the electronic levels is negligible. This reflects the fact that the correction acts primarily through a curve with almost the same effect on the two extreme methods.

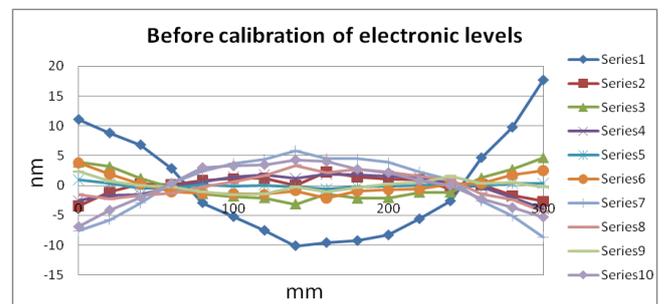


Figure 14 : Repeatability of 10 acquisitions

Figure 14 shows the repeatability of 10 acquisitions of the same profile after capacitive sensors calibration but not the level of sensor preponderant method. The plotting is the difference of each profile in compared with the average profile.

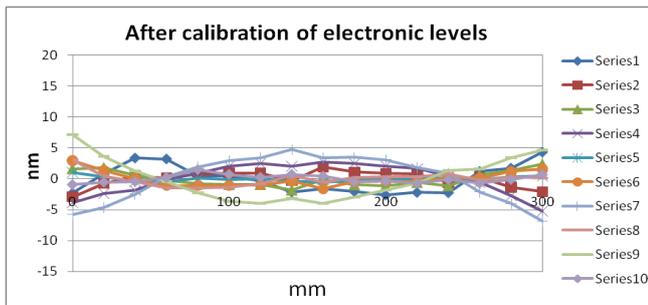


Figure 15 : Repeatability of 10 acquisitions

The level correction is incorporated. Figure 15 shows that the repeatability of 10 measurements is improved by the levels calibration. This is due to the fact that the movement of the scanning stage is not repeatable, which means that the electronic level is applied over a range larger or smaller depending on acquisitions. The calibration of the level depends on the consideration of the rotation seem as a component of repeatability which is not a classic idea.

Figure 15 shows a coherence of the results of about ± 5 nanometers, which includes all the acquisitions and calibration.

To go further, it was necessary to establish the weighted least squares method. The final calculation of uncertainties using the method of Monte Carlo [7] results in ± 10 nm.

Conclusion

The results of the profiles (Figure 15) shows that we obtain a reproducibility in the order of ± 5 nm of 10 acquisitions.

The calibration of capacitive sensors has a very significant effect probably because of the propagation which accumulates the uncertainties.

The calibration of electronic levels does not reduce the discrepancy between the profiles from the two solutions because it is in fact a curve which is identical for both counting techniques. However, the calibration of level saves about thirty nanometers in reproducibility by decreasing the dispersion of the curvature corrections.

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