Investigation on the thermal behaviour of an ultra-high precision system used in dimensional metrology

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Abstract

The LNE is currently developing a new cylindricity measurement apparatus with a nanometric precision [1]. Its architecture respects both the Abbe and the dissociated metrology structure principles. The metrology frame is symmetric and compacted as possible to be less sensitive to thermal drifts. The accuracy of the cylindricity apparatus depends on the performance of the reference capacitive probes aligned on a reference cylinder and on the thermal stability of the metrology frame.

In order to validate the design of the machine, an experimental set-up insuring the in-situ calibration of 4 capacitive sensors was developed; its operating mode is detailed in the following. Both the step-by-step and continuous calibrations of the capacitive probes were performed. The data issued from the probes were compared to the information given by four laser interferometers aligned on the same Abbe point as the capacitive probes. The residual errors were calculated, illustrated and discussed here.

In the second part of the paper, the thermal stability of the bench is addressed. A thermomecanichal study was carried out using a software based on finite elements called COMSOL Multiphysics. Two cases were considered for the experimental set-up respectively with and without protection shell. The study allowed the identification of the most sensitive zones of the set-up that should be controlled.

1. Experimental set-up and context

In dimensional metrology, measurements are usually done in a controlled environment. The temperature is controlled to $20^{\pm 0.3}$ °C and the relative hygrometry to $50^{\pm 5}$ %RH. However, some of the machine components dissipate heat which induces thermal expansion of the metrology frame and affect the uncertainty. To deal with thermal variation issues, a control must be implemented [2].

Since the metrology frame is the most sensitive part of the machine, instead of studying the entire system, the experimental set-up developed initially to investigate in-situ calibration will be used for the study. Then, the results will be extended to the machine. The set-up given by Figure 1 is composed of 4 capacitive sensors aligned on a cylindrical artefact, 4 low consummation laser interferometers from Renishaw@ which are aligned on 4 independent plan mirrors, fixed on the XY table through isostatic links. The XY table is equipped with 2 piezoelectric actuators under two levels. The motion is insured by four flexible blades over a travel range of 80 µm, but this range can be increased until 180 µm. The laser interferometers, which are considered as reference sensing elements, are fixed on the supporting structure with an angular shift of 45° to the capacitive probes fixed in the metrology frame. This arrangement of the laser interferometers improves the uncertainty by a ratio of $\sqrt{2}$.

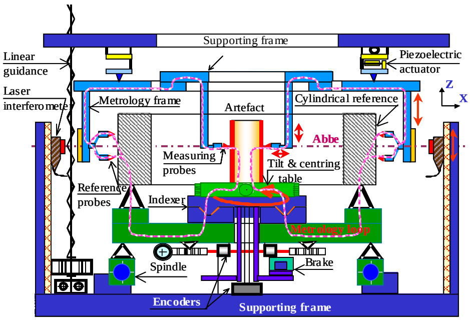

Figure 1: (a) schema of the ultra-high precision cylindricity apparatus

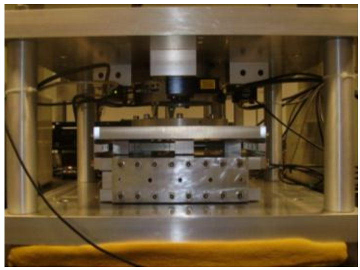

Figure 1: (b) Photography of the developed experiment-setup

2. Results

2.1 Calibration of the capacitive sensors

The calibration is performed by varying the gap between the sensing electrode of the capacitive probe and the cylindrical artefact in a dynamic or a step-by-step mode. The first calibration test is performed over a travel range of 80 µm by a step of 2 µm. The motion is generated thanks to the flexible blades, and is tracked by the four laser interferometers traceable to the SI meter definition. The data given by each capacitive probe are compared to those given by the laser interferometers. The obtained residual errors when applying the calibration step-by-step is within ±2.5 nm (Figure 2(a)). These results of the residual errors are lower than those obtained with the continuous mode (within ±5 nm) (Figure 2(b)). However, similar results can be obtained with the continuous mode by applying a moving average to the data.

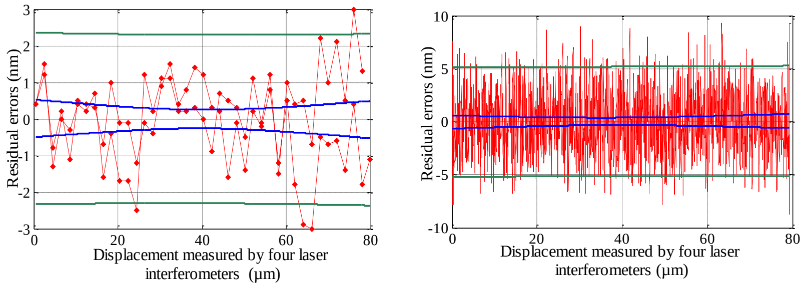

Figure 2: (a) Evaluation of the residual errors: static mode , (b) Evaluation of the residual errors according to the displacement : dynamic mode

The results above are sufficient for obtaining the targeted nanometer level of accuracy. They were obtained by adding an aluminium protection shell to the test bench. A thermo mechanical study was conducted to evaluate the benefits of introducing such protection to the set-up.

2.2 Thermo mechanical study

A time dependent simulation was conducted with COMSOL software. The boundary conditions were selected to respect the working conditions of the set-up such as the surrounding temperature of 20 °C. The convective coefficient was fixed to $h = 7W.m^{-2}.K^{-1}$. The heat dissipated by the four Renishaw@ laser interferometers was considered as disturbance. The power dissipated by each laser is 0.14 Watt. The aluminium is selected for all the parts, with a dilatation coefficient of 22 µm/°C/m. The mesh of the setup was adjusted to the volume of each element. The resolution of this problem was performed over a range time of 20 hours.

As results, it appears that the magnitude of the temperature inside of the setup without the protection shell is higher than it is with a protection shell (Figure 3(a)). Figure 3(b) shows the stress distribution which is concentrated on the metrology frame in the absence of the protection shell. However for the second case the stress is concentrated on the protection shell itself.

For a high precision machine based on the dissociated metrology frame principle, the thermal expansion of the supporting frame is not significant, but the asymmetric thermal dilatation of the metrology frame should be reduced and controlled.

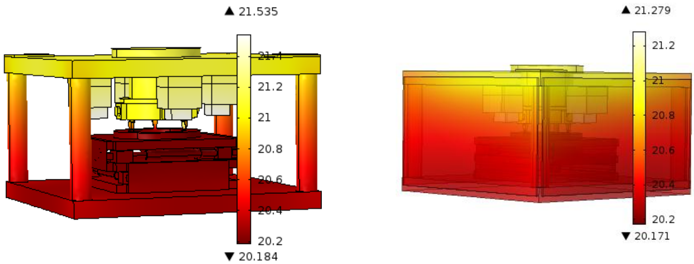

Figure 3(a): Temperature distribution with and without protection shell

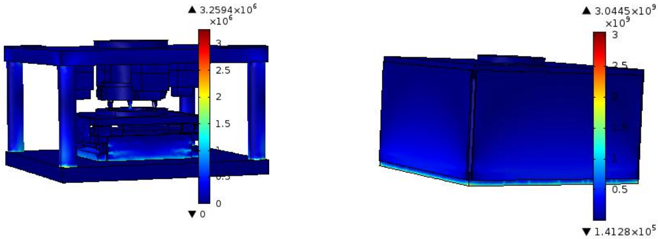

Figure 3(b): Stress distribution with and without protection shell

3. Conclusion

Calibration results for step-by-step and continuous modes of the capacitive probes were presented. These results were obtained by adding a protection shell to the experimental set-up. The step-by-step mode calibration residual errors (±2.5 nm) are lower than the continuous mode calibration residual errors (±5 nm), but it is possible to obtain similar results by applying a moving average.

The thermo-mechanical simulation was conducted with COMSOL software for two cases (without and with protection shell). The obtained results revealed the benefit of using a protection shell on the temperature stability. The distribution of the mechanical deformation when a protection shell is added to the set-up is concentrated on the protection shell instead of the metrology frame.

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References:

[1] A. Vissiere, H. Nouira, M. Damak, O. Gibaru, J-M David Concept and architecture of a new apparatus for cylindrical form measurement with a nanometric level of accuracy, Meas. Sci. Technol 23-9 (2012).