Metrological characterization of optical confocal sensors measurements (20 and 350 travel ranges)

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Abstract. Confocal sensors are usually used in dimensional metrology applications, like roughness, form, thickness and surface profile measurements. With the progress of technologies, metrological applications require measurements with nanometer-level of accuracy by using ultra-high precision machines, which should present a minimum and stable metrology loop. The loop is equipped with sensors with nanometer-level of resolution and linear residual. The study presented here, is mainly focused on the characterization of Confocal sensors in order to identify their performance practically. Such information is useful to establish a correction model in the digital signal processing (DSP) software. In this context, LNE developed an ultra-high-precision machine, dedicated to the roughness measurement with an uncertainty of a few nanometres (< 30 nm) by using a tactile sensor. In order to match this machine to Confocal sensors, an experiment has been recently developed to characterize the behaviour of two commercial Confocal sensors with the measuring range of 20 µm and 350 µm. The experiment permits the evaluation of the major error sources: axial and radial motion errors as well as the deviation/tilt of the sensors.

1. Introduction

Confocal chromatic probes are widely used in mechanical industry and prove to operate at fast rates to measure any error of form, roughness, profile and thickness, as well as they are distinctively transparent to surface deformation.

The working principle of confocal chromatic probes for surface profiling is reported in [1-3]. We usually deal with a white light source (LED), in which the spectral components are focused at different distances along the optical axis. The reflected light is collected and analyzed with a spectrometer (diffraction grating).

The large use of confocal probes creates the need for a serious study of their limitations and performances. The calibration of such probes is usually achieved by comparing the confocal probe’s measurement with a second measurement serving as a reference. Boltryk et al [4-5] conducted experiments and compared optical measuring techniques on a cylindrical artefact with sinusoidal grooves. Confocal and triangulation laser probes are tested along with a stylus profilometer as a reference for comparison. Results reveal that confocal probe measurements are slower but more accurate than triangulation probes.
This paper summarizes the characterization of two confocal probes with a measuring range of 20 and 350 µm. A test bench was specifically designed to ensure that measurements exhibit a nanometric level of accuracy. The linear residuals of the confocal chromatic probes are investigated with different materials and colour paints. The effect of the inclination, roughness, speed and error related to the artefact geometry are also detailed.

2. LNE ultra-high precision profilometer for 3D measurement

The 3D apparatus performs three independent motions (x, y and z) generated by three independent high-precision mechanical guiding systems equipped with encoders. The horizontal (x and y) guiding systems support the table made of zerodur material, and is able to move along both the x- and y-axes in dynamic or static operation. The vertical guiding system moves the structure supporting the measuring probe along the z-axis. Each x- and y-motion is controlled by a laser interferometer in order to locate the part at the nanometre level of accuracy. The z-motion is controlled by a differential laser interferometer to shorten the metrology loop [6]. The supporting structure is made of massive granite materials and support all the guiding systems. The metrological structure, represented with blue colour in Figure 1(a), is made of Invar material and is less sensitive to the environment and to structure thermal deviation. Any vertical variation of the main granite structure (1) by both thermal drift and its own mass slightly influences the metrological structure with few nanometres. This variation is indirectly compensated by the differential laser interferometer.

The architecture of the machine perfectly respects the Abbe principle [7] along all the axes. The measuring single scanning probe is collinear with the differential laser beam (2) and represents the “measuring Abbe Z-axis”. The horizontal x- and y-laser interferometer beams and the touching element of the tactile probe are designed to be in the same XY-plane and axis (Abbe x- and y-axes). These Abbe axes never change because the measuring probe and the x- and y-laser interferometers are fixed on the same Invar metrological structure. By that, any vertical motion of the metrological structure induces a similar vertical motion of the x- and y-laser interferometers and the measuring probe. Each laser interferometer is fixed on an intermediate mechanical structure to ensure two motions and one rotation of the laser head in order to adjust the alignment of the laser beam on each respective mirror.

The entire x- and y-working range is equal to 50 mm. The z-working range can reach 100 mm. In-situ calibration of the measuring probe can be achieved by moving the metrological structure which contains the tactile probe along the z-axis with perfect respect of the Abbe principle.

![Diagram of the profilometer](image1.png)

**Figure 1.** (a): Architecture of the ultra-high precision profilometer, (b): Photograph of the apparatus
The performance of the LNE profilometer depends on both the behaviour of the measuring probe and the quality of the mechanical guiding systems, which is reduced by using the reference laser interferometers. The current configuration of the machine allows measurements of the target with a tactile single scanning probe. For a working range of the tactile probe of 150 µm the evaluated uncertainty is estimated to 30 nm.

In some applications such as the metrological characterization of optical aspherical lenses with an accuracy of few tenths of nanometres, it is interesting to use an optical scanning probe instead of a tactile probe in order to avoid any deformation or scratching of the part’s surface coating. In this way, two optical confocal scanning probes are selected for the application and need to be qualified. According to the behaviour of the such probes, corrections have to be taken into account in the software.

3. Error sources in displacement measuring confocal probes

The main degrees of freedom that impact the measurement and are worth being evaluated are:

- translation ($T_x$) along the x-axis: it corresponds to the axial motion of the confocal probe with respect to a flat artefact. The evaluation of $T_x$ allows the characterization of both the linearity and the sensitivity of the probe.
- translation ($T_y$) along the y-axis: this degree of freedom corresponds to the transverse motion of the confocal probe axis from the generator of the cylindrical artefact. The evaluation of $T_y$ gives an idea about the influence of the transverse motion error on the measurement.
- rotation ($R_y$) along the y-axis: this degree of freedom corresponds to the inclination of the confocal probe axis with respect to the horizontal orientation by an angle of $\phi$.

![Diagram](image)

Figure 2. Description of the different tests

The interaction probe-material, roughness, speed and geometry of the artefact impact the behaviour of the probe, and are investigated here. To complete all these tests, four experiment configurations are devised as described in Figure 2(a, b, c and d). Note that when using flat artefacts, the motions along the x and y-axes are named respectively axial and transverse motions. When using cylindrical artefacts, the motions along the x, y and z-axes are named respectively radial, transverse and axial motions.
4. Description of the experimental test bench

The design of the test bench ensures two independent motions along the x and y-axes and two rotations around the z and y-axes. Along the x-axis two independent mechanical motions can be generated by using two independent and superposed mechanical stages. The first one produces a micrometric motion step over 63 mm range. The second stage incorporates a piezoelectric actuator, which is used with an electronic feedback, and a mechanical structure based on flexible blades to limit any hysteresis phenomenon. It generates nanometric motion steps of 5 nm over 90 µm entire range. A precision mechanical linear stage equipped with a stepper motor ensures the motion $T_y$ over 50 mm range with a minimum incremental motion of 0.1 µm.

![Figure 3. Architecture of the test bench](image1)

![Figure 4. Photograph of the experimental test bench](image2)

A manual rotary stage based on flexible blades guarantees the rotation $R_y$ of the confocal probe over a working range of ±3° and a second manual rotary stage ensures the rotation $R_z$ of the target over a working range of 180° (Figure 3 and Figure 4).

The design of the test bench applies the Abbe principles along both the x- and y-axes. The Abbe x-axis is mingled with the x-axis laser beam in correspondence with the confocal probe’s axis when perfectly oriented horizontally. The Abbe y-axis is collinear to the y-axis laser interferometer beam.

Two laser interferometers with sub-nanometric resolution are used to measure the generated displacements $T_x$ and $T_y$ of two Zerodur plane mirrors. These mirrors have an overall flatness of $\lambda/20$. The perpendicularity of the mirrors surfaces to their respective laser beam axes is insured by a nanometric sensitive contact probe. The parallelism of the confocal chromatic probe and the x-axis
laser, as well as the perpendicularity between the x-axis and y-axis laser interferometers are carried out carefully by CMM measurements.

The architecture of the test bench perfectly applies the dissociated metrological structure principle [6]. Block (1) supporting the x-axis laser interferometer is decoupled from block (4), made of aluminium, by using flexible blades. Two Invar rods have been mounted to rigidly link both blocks (1) and (2) and shorten the metrology loop [6]. Hence, any thermal expansion and mechanical deformation of block (4) never influences the metrology loop. Block (3) is also made of Invar, which improves the stability of the metrological structure.

The experiment is performed inside the LNE clean room, where both temperature and humidity are controlled to 20±0.3 °C and 50±5 %HR, respectively. The experiment is also enclosed in an aluminium shell and installed on the anti-vibration structure.

All the motions and acquired data are controlled by a developed LabView program. A synchronous record of the laser interferometers, confocal probe, temperature, hygrometry and pressure data are carried-out during the test. The environment parameters are used to introduce correction for the refractive index of air (updated Edlen formula [8] and dead-path [9]).

5. Experimental results

5.1. Metrological Analysis
Two kinds of errors that influence the measurement can be distinguished: systematic errors that can be characterized and compensated, and random errors that are merely random (incorrugible errors). The qualified systematic errors correspond to the thermal expansion of the test bench, thermal variation of the refractive index of air, cosine errors, Abbe errors and resolutions of the laser interferometer and confocal chromatic probe. The analysis of these errors reveals that the resolution of the confocal probe presents the most important contribution of 12 nm. However, the test bench presents a nanometric level of accuracy (<5 nm), when the working range doesn’t exceed 90 µm.

5.2. Stability of the 20 µm confocal chromatic probe
To accurately characterize the probe, the stability of the laser interferometer and the stability of the confocal probe are firstly studied over half an hour and reveal ±2 and ±20 nm of variation, respectively (Figure 5).

5.3. Effect of the material and colour on the linearity of the probe
The linearity tests are performed with different kinds of materials (aluminium, steel, gold, copper, silicon and ceramic) with respect to Figure 2(a). They have different absorption and reflection values according to the wavelengths in the white light source. The reflectance values of the selected materials
are respectively equal to: 93%, 53%, 92%, 60%, 30% and 95%. From Figure 6, the gold-deposit mirror has large linear residuals, values near the start seem to be “compressed” and the useful range for the gold-deposit mirror is not so large as compared to other materials. Ceramic materials show low linear residuals (less than 40 nm) but are limited to the smallest travel range compared to all tested materials. The other four materials, silicon, copper, steel and aluminium behave approximately the same and exhibit similar linear residuals (between –150 and 200 nm) with a large working range.

Figure 6. Linear residuals versus displacement along x-axis (material)

Since the observed behaviours are different in Figure 6, the impact of colour is then investigated. Five colour paints for the same steel material are chosen for these tests: yellow, silver, red, blue and green. The recorded linear residuals are illustrated in Figure 7 and show dissimilar behaviours. For red, all wavelengths are absorbed except the one corresponding to the red colour, that’s why there is no signal for the red colour sample from 0 to 9 µm. It means that the 380-500 nm wavelengths, which correspond to the partial range until 9 µm, match with blue and violet colours. For yellow and silver, they behave the same as the gold-deposit and aluminium-deposit mirrors, which proves that a certain amount of wavelengths is absorbed by the tested artefacts. These results confirm that the confocal probe’s behaviour depends on the colour rather than on the material.

Figure 7. Linear residuals versus displacement along x-axis (colour)

5.4. Impact of the roughness of the aluminium artefact
The linearity of the confocal chromatic probe is investigated with three selected rough flat artefacts made of aluminium and measured by the LNE ultra-high precision profilometer for roughness
measurements. Table 1 gives the average of 16 measurements of the Rz parameter (ISO 4287:1997) and the standard deviation ($\sigma$).

**Table 1. Roughness of the tested aluminium materials**

| Roughness parameter | Roughness of | Standard deviation | $\sigma$ ($\mu$m) |
|---------------------|--------------|--------------------|-------------------|
| Aluminium deposit   | 0.020        | 0.0004             |
| Aluminium R1        | 2.50         | 0.15               |
| Aluminium R2        | 4.40         | 0.70               |
| Aluminium R3        | 6.50         | 0.50               |

From Figure 8, it is obvious that the effective working range depends on the roughness of the artefact. Then, adding roughness induces a less effective working range. As a consequence, the linear residuals vary according to the change of the effective working range change. This observation is also related to the power density spectrum. For instance, at the beginning of the travel range, the power density could not reach its sufficient level which lead the power spectrometer to fail to detect the signal.

**Figure 8. Linear residuals versus displacement along x-axis (roughness).**

5.5. Influence of the inclination of the 20 $\mu$m confocal probe

The influence of the inclination is investigated here in order to be able to estimate the correction to be taken into account when the probe is focussed on a part with one slope and/or v-groove or/and cylindrical and/or aspherical shapes.

The impact of the angle $\phi$ between the probe and the flat artefact is investigated within the range of $\pm 16^\circ$, as shown in Figure 2(b). For each test, the parameters of linearization are identified and the linear residual is deduced. Since the results from $0^\circ$ to $-16^\circ$ are symmetric to the ones between $0^\circ$ and $16^\circ$, only results from $0^\circ$ to $16^\circ$ are presented in Figure 9.

At $0^\circ$, the linear residuals are between $\pm 150$ nm. With the increase in angle, the linear residuals decrease to less than $\pm 50$ nm at $6^\circ$, then increase again. Up until $16^\circ$, the linear residuals vary in-between -600 and 130 nm. This observation is related to the power density of each wave reflected back into the spectrometer (diffraction grating).
5.6. Influence of the artefact geometry and transverse offset

The linearity tests are completed when the confocal chromatic probe is well aligned on the generator of the cylindrical artefacts with diameters of 50 and 75 mm as presented in the Figure 2(c).

![Figure 9](image-url) Linear residuals versus displacement along x-axis (inclination).

![Figure 10](image-url) Linear residuals of 50 mm cylinder, 75 mm cylinder and flat artefact versus displacement along x-axis.

From Figure 10, both the working range and linear residuals of the confocal chromatic probe are higher when it is focused on the steel flat artefact. However, if we consider the same measuring range for all tests, the linear residuals perform perfectly the same. It means that the linear residuals variations are due to the effective working range change.

As the confocal probe is integrated into the high-precision profilometer which is equipped with mechanical guiding systems [6], the guided movements are never achieved perfectly and usually present repeatable and un-repeatable transverse, axial and radial error motions. The amplitude of these error motions varies according to the adopted technology for the linear mechanical guiding systems. Therefore, when the artefact presents cylindrical or/aspherical or/and freeform shapes, the probe has to be qualified before any measurement in order to estimate the effect of errors in relation to the combination of both motion and shape.

Tests are completed by moving the confocal probe, while it is focussed on cylindrical artefacts, along the y-axis and over a range of ± 200 µm. The position corresponding to y = 0 µm represents the probe when it is well focused on the generator of the cylindrical artefact. The experimental results are
compared to the theoretical model detailed in [6], obtained when the probe undergoes a transverse motion and is located at position (B) instead of position (A) (Figure 11).

To complete the transverse offset tests, the value of the gap is fixed and only the transverse motion is generated as presented in Figure 2(d). The tests are achieved with three values of the gap (distance between the probe and the artefact): 7, 12 and 17 µm, and two cylinder diameters: 50 and 75 mm. The experimental results are compared to the theoretical results obtained with a cylinder diameter of 50 mm and shown in black in Figure 12. Results are presented according to y-displacement measured by the y-axis laser interferometer, perpendicular to the confocal probe’s axis. A good agreement between the model and the experiment is observed despite the noise, which is slightly high.

Figure 11. Description of the transverse offset test

Figure 12. Influence of the artefact geometry on the confocal probe measurement (C75, 7 µm cylinder diameter of 75 mm, gap of 7 µm) versus displacement along y-axis

Figure 13. Evolution of the linear residuals when the confocal probe is used in dynamic mode: speed values of 0.1, 0.2 and 0.3 µm/s
On CMM, confocal probes can be used in quasi-static or dynamic modes, that is why the impact of the motion speed of the artefact on the behaviour of the probe is explored. Three values of the speed were selected between 0.1 and 0.3 µm/s. When the motion speed increases, the number of acquisitions deceases. It is the reason why it is impossible to reach high speed values.

The obtained linear residuals are similar (±200 µm) and in the same order as the previous linear residuals obtained when the probe is employed in the quasi-static mode (Figure 6). However, the travel range is reduced and is equal to 14 µm (Figure 13) instead of 17 µm as before.

5.7. Confocal chromatic probe of 350 µm range

The confocal probe of 350 µm range is characterized under similar conditions. Only results concerning linear residuals evolution when changing the part materials is presented her. Figure 14 reveals that the linear residuals vary between ± 600 nm. The behaviour of the confocal probe of 350 µm is summarized in Table 2.

![Evolution of the linear residuals vs. the laser data for different materials of the target (0 - 350µm)](image)

**Table 2. Comparison of the confocal probe of 20 and 350 µm range**

| Confocal probe of:         | 350 µm | 20 µm |
|----------------------------|--------|-------|
| Stability                  | 100 nm | 20 nm |
| Linear residuals           | ± 400 nm | ± 150 nm |
| Effect of materials        | Not sensitive | Not sensitive |
| Effect of colours          | Not sensitive | sensitive |
| Effect of roughness        | Not sensitive | Not sensitive |
| Effect of inclinations     | Not sensitive | sensitive |
| Effect of transverse offsets | Not sensitive | Not sensitive |
| Effect of speeds           | sensitive | Not sensitive |

The confocal probe of 350 µm is in-situ calibrated again on the ultra-high precision profilometer with different values of the speed. 2048 linear models and parameters of linearization are calculated separately over 2048 partial ranges to cover the whole travel range of 350 µm. The linear residuals are obtained for the entire travel range and results are presented in Figure 15. The linear residuals are less than 14 nm at the beginning of the travel range (0 µm) and decrease to 4 nm at the travel range’s end (350 µm).
By using this technique it is possible to reduce the values of the linear residuals to few nanometres which is very beneficial when performing measurements at the nanometric level of uncertainty. However, this solution needs to be able to process a large number of linear models and parameters of linearization in real time.

**Figure 15.** Linear residuals versus displacement along x-axis (speed)

The variation of the speed from 10 to 100 µm/s does not influence the evaluation of the linear residuals, which means that it is possible to perform quick measurements with similar level of accuracy. When using the confocal sensor of 350 µm over a partial travel range of 150 µm the uncertainty is evaluated to 60 nm.

6. Conclusion

In this paper a novel approach to characterize confocal probes with nano-scale level of accuracy was proposed. A new developed test bench has been used to perform different experiments that are related to different error sources impact parameters: material, roughness, colour, inclination angles, target geometry and speed. The basic design principles are respected: the metrology loop is optimized, the Abbe principle is respected and specific materials are carefully selected. The results reveal that the confocal probe with a travel range of 20 µm is more sensitive to colours and less sensitive to materials. The impact of the geometry on the behaviour of the confocal probes is also investigated by using two cylindrical artefacts with the diameters of 50 and 75 mm, respectively. So, when the diameter of the artefact decreases, the amplitude of noise increases, and inversely. The impact of the motion speed is also investigated and can also influence the linear residuals and the working range of the confocal probes.

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8. References

[1] Hocken R J, Chakraborty N and Brown C 2005 Optical metrology of surfaces *CIRP Ann.* **54** 705–719

[2] Weckenmann A, Jiang X, Sommer K, Neuschafer-Rube U, Seewig J, Shaw L and Estler T 2009 Multisensor data fusion in dimensional metrology, *CIRP Ann. Manuf. Technol.* **58** 701–721.

[3] Cohen-Sabban J, Gaillard-Groleas J and Crepin P J 2001, Quasi confocal extended field surface sensing. *Proc. SPIE* **4449** 178-183.

[4] Boltryk P J, Hill M, Mcbride J W and Nasce A 2008 A comparison of precision optical
displacement sensors for the 3D measurement of complex surface profiles Sens. Actuators A 142 2–11.

[5] Boltryk PJ, Hill M and Mcbride J W 2009 Comparing laser and polychromatic confocal optical displacement sensors for the 3D measurement of cylindrical artefacts containing microscopic grooved structures Wear 266 498-501.

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

[7] Abbe E 1890 Meßapparate für Physiker Zeitschrift Fur Instr. 10 446 – 448

[8] Birch KP and Downs M J 1993 An updated Edlen equation for the refractive index of air Metrologia 30 155-162.

[9] Stone J, Phillips S and Mandolfo G 1996 Corrections for Wavelength Variations in Precision Interferometric Displacement Measurements J. Res. Natl. Inst. Stand. Technol. 101 671-674.