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Influence of surface location within depth of field on measuring by a conoscopic holography sensor integrated in a machining centre

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Abstract

In this work, a Conoscopic Holography (CH) sensor integrated in a Machining Centre (MC) was used for analysing how the measurements taken are influenced by the location of the digitized surface within depth of field (DOF). With this aim, two different digitizing strategies were conducted on a stepped specimen with flat surfaces. In the first strategy each step of the specimen was located at different positions within DOF whereas the CH sensor was kept at a constant height along the scanning of all steps. In the second strategy the sensor height was adapted so that each step was scanned at the same distance within DOF. The comparison between both strategies was performed by calculating the discrepancies between measurements taken by the CH sensor and those obtained by a touch probe (TP) also installed in the MC. Finally, the study provides a series of recommendations for practical application of the sensor.

1. Introduction

Industrial use of commercial scanners like non-contact digitizing systems has grown significantly in recent years with a wide range of applications that go from dimensional metrology to reverse engineering [1]. Apart from avoiding contact with the object to be measured, the main advantages over contact systems are the ability to capture small geometries and complex shapes as well as the high speed for points acquisition. Additionally, the portability of

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non-contact systems offers the possibility to be installed on different equipment such as coordinate measuring machines (CMM), coordinate measuring arms, machine tools or production systems, which certainly favours its industrial application.

Currently, there exist numerous non-contact techniques for surface digitizing, such as those based on triangulation laser which are more deeply analysed and disseminated every day [2-4]. However, the performance of other technologies has not been fully described yet. This is the case of Conoscopic Holography (CH).

CH is an interferometric technique based on the double refractive property of birefringent crystals. It was first described by Sirat and Psaltis [5] and patented by Optimet Optical Metrology LTD. When a polarized monochromatic light ray crosses the crystal, it is divided into two orthogonal polarizations, the ordinary and extraordinary rays, which travel at different speeds through the crystal. The speed of the ordinary ray is constant. However, the speed of the extraordinary ray depends on the angle of incidence. In order to make both rays interfere in the detector plane, two circular polarizers are placed before and after the crystal. The interference pattern obtained in the detector has a radial symmetry, so that all the information is contained in one radius. Therefore, given an appropriate calibration, it is possible to calculate the original distance to the light emitting point from the fundamental frequency of one of the signal rays.

Potential of CH as a valuable alternative to current well-established technologies (laser triangulation or photogrammetry) has led researchers to work on analysing the performance of CH sensors under different scanning conditions [6-11]. Malet and Sirat [6] stated that the performance of a conoscopic system can be influenced by the depth of field, speed and transverse resolution. Sirat et al. [7] denoted characteristics of CH like accuracy and repeatability, good behaviour for a wide variety of materials and for slope surfaces measuring. The ability of CH for digitizing highly sloped surfaces was also highlighted by Ko and Park [8]. Furthermore, CH sensor performance is affected by surface properties, as it was highlighted by Lathrop et al. [9] who analysed different types of biological tissues to demonstrate that the nature of surface material (colour, roughness, texture) has an influence on the digitizing quality. In the same field, Lonardo et al. [10] or Lombardo et al. [11] analysed the influence of roughness surface.

Among other influencing factors and from a practical point of view it is important to know whether the quality of points acquired by a CH sensor in a digitizing process is dependent or not on the location of the surface within the DOF of the sensor. This will become an essential factor to know whether it is advisable or not to modify the relative distance between the sensor and the surface during the digitizing process as well as to determine the number of scanning passes necessary for a complete surface digitizing.

With this aim, in the present work, a CH sensor integrated in a Machining Centre (MC) was used for analysing how the measurements taken are influenced by the location of the digitized surface within depth of field (DOF). A stepped specimen was designed and digitized under two strategies. In the first strategy all the steps are scanned keeping the sensor at a constant height with regard to the MC table. This way, each step will be located at different heights within DOF. In the second strategy the sensor height is adapted so that each step shall be scanned at the same distance within DOF. The comparison between the results of both strategies will enable to analyse the influence of surfaces location within DOF. The results were analysed by calculating the discrepancies between measurements taken by the CH sensor and those obtained by a touch probe (TP) installed in the MC. Finally, the study provides a series of recommendations for practical application of the sensor.

2. Experimental equipment

The work described in this study was performed on a Machining Centre (MC) model Lean L1000 equipped with a FANUC M0i control. The contact measurements were carried out by means of a touch probe (TP) Renishaw OPT400 integrated in the MC which is controlled through the macros by this manufacturer.

On the other hand, non-contact measurements were performed by means of the conoscopic holography (CH) sensor Optimet Conoprobe Mark III which was installed into the MC spindle by means of an ad hoc adaptor (Fig. 1). It is externally operated from a PC through an interface based on the FOCAS2 libraries (Fanuc Open CNC Api Specifications), which enable to synchronize the measurement capture with the position of the MC axes. To make a measurement, the application sends to the CNC the coordinate of the point to go and the movement order. When the
target position is reached, the application sends to the CH sensor an order to take the measurement. This process is repeated for all points to be scanned.

Fig. 1. Measurement of the specimen by means of the TP and the CH sensors on the MC.

2.1. Characteristics of the conoscopic holography sensor

The Conoscopic Holography (CH) sensor Optimet Conoprobe Mark III was equipped with a lens of 50 mm focal length, with a DOF of 8 mm. The visible light source is a Class II laser diode with a wavelength of 655 nm. This is a point-type sensor, thus each reading provides the value of the distance from the transmitter to the projection of the laser beam on the material surface (spot). Table 1 shows the main characteristics of the sensor [12].

<table>
<thead>
<tr>
<th>Property (Lens 50 mm)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions (L × W × H) (mm)</td>
<td>80 x 180 x 60</td>
</tr>
<tr>
<td>Weight (g)</td>
<td>750</td>
</tr>
<tr>
<td>Measuring frequency, F (Hz)</td>
<td>up to 3000</td>
</tr>
<tr>
<td>Power level, P (^1)</td>
<td>0 – 63</td>
</tr>
<tr>
<td>Depth of field, DOF (mm)</td>
<td>8</td>
</tr>
<tr>
<td>Stand-off (mm)</td>
<td>42</td>
</tr>
<tr>
<td>Precision (^2) (µm)</td>
<td>&lt;6</td>
</tr>
<tr>
<td>Reproducibility 1σ (^3) (µm)</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Angle measurement (^4) (°)</td>
<td>170</td>
</tr>
</tbody>
</table>

\(^1\) Maximum power level (63) is equivalent to 1 mW  
\(^2\) Twice the maximum error when measuring a step located at 5 to 6 different positions throughout the DOF  
\(^3\) As measured on a flat diffusive metallic surface, average of 5 scans offset in “y” direction. Minimum sampling step \(\frac{1}{2}\) of the spot size, average over 200 points in each scan. Measured over a step higher than 50% of the DOF  
\(^4\) Measurable points up to ±85° from normal incidence angle

2.2. Setting parameters of the conoscopic holography sensor

There are two main setting parameters in a CH sensor Conoprobe Mark III:
Power Level \((P)\) represents the value of the laser beam energy used and can be set up in a range from 0 to 63, where 63 is equivalent to 1 mW of power.

Working Frequency \((F)\) represents the data acquisition rate and can be set up to a maximum of 3000 Hz.

For a given frequency \(F\), the value of power \(P\) has to be adjusted so that a proper amount of energy reaches the sensor. Two quality indicators of the signal acquired should be observed for this purpose:

SNR (Signal-to-Noise Ratio), that is calculated by comparison of the peak power value used for the measurement to the whole signal power, which includes signal noise. SNR may range from 0% to 100% and it is commonly assumed that the higher the SNR, the higher the accuracy of measurement. Reliable values of SNR should be above 50%.

Total, that is proportional to the area limited by the signal envelope and increases as signal intensity does. Acceptable values of Total should be between 1200 and 16000 [12].

3. Experimental procedure

A stepped specimen was used to analyse the influence of the position of the surface to be scanned within DOF. This way, it was possible to compare distances between flat surfaces located at different positions within DOF which were taken by means of the two sensors (TP and CH). On the one hand, the distances between adjacent steps were measured in order to compare the measurement of a same magnitude at different locations within DOF. On the other hand, distances were measured between each step and a reference one (datum step) located at the stand-off. Thus, it was possible to realize how it changes the discrepancy between the CH and TP when magnitudes of different nominal value are measured within DOF. The scanning process with the CH sensor was performed under two different strategies. In the first, the height position of the sensor was kept constant along the scanning of all the steps \((Z_{\text{const}})\). In the second strategy, the height position of the sensor was modified for each step so that the digitizing distance was coincident with the stand-off in all the cases \((Z_{\text{var}})\).

The stepped specimen used was manufactured on stainless steel (AISI 316) by wire EDM for minimizing geometrical distortions. The specimen includes 21 parallel flat steps of 30 x 12 mm of area (Fig. 2). The nominal height of each step is 0.5 mm, so that a total range of \(\pm 5\) mm can be analysed with respect to a reference intermediate step located at the middle of the specimen (datum step). Additionally to the steps, the specimen includes two flat surfaces coplanar with the datum step which will be used for alignment purposes.

![Fig. 2. Positioning of the stepped specimen within the depth of field (DOF).](image-url)
The experimental procedure was carried out through the following stages:

The specimen was attached to the MC vise taking care that the test surfaces of all the steps were parallel to the XY reference plane of the MC (Fig. 1).

Calibration of the TP on a sphere of diameter 20 mm by means of a specific macro of 3D Form Inspect by Hexagon Metrology.

Digitizing of the alignment surfaces (S1 and S2) by capturing 100 points on each of them by means of the TP.

Digitizing of the steps 3 to 17 by the TP. Fifteen points distributed within a rectangular mesh of 5x3 mm were captured on each step. Thirty repetitions were performed to assure repeatability.

Calibration of the CH sensor on the same sphere used with the TP. The procedure used is based on works by Fernández et al. [13] and K. B. Smith [14].

Adjustment of the CH sensor height until datum step of the specimen coincides at the stand-off distance (Fig. 2).

Digitizing of the alignment surfaces (S1 and S2) by capturing 100 points on each of them by means of the CH.

Digitizing of the steps 3 to 17 by the CH sensor which is kept at a constant height with regard to the MC table.

Fifteen points distributed within a rectangular mesh of 5x3 mm were captured on each step. Thirty repetitions were performed for repeatability analysis.

Digitizing of the steps 3 to 17 by modifying the height position of the CH sensor for each step so that the digitizing distance was coincident with the stand-off in all the cases. The number of digitized points and repetitions were identical to those of the previous stage.

Prior to perform the tests by the CH sensor, the values of frequency $F$ and power $P$ were determined in order to acquire an optimal signal according to the manufacturer recommendations (SNR > 50% and 1200 < Total < 16000). This way, the best combination found was ($F_{2000}, P_{15}$) which was used for tuning the CH sensor in the next stages of the experimentation.

4. Analysis of results

The analysis of results was based on the comparison of distances between steps scanned by the CH sensor with regard to those scanned by the TP. Distances $d$ between adjacent steps (step-step) and distances $D$ from each step to a reference one (step-datum) were compared. Since the measurements performed by the TP will be used as reference, a repeatability analysis of both types of distances was initially carried out. With this aim, 15 points were digitized on each specimen step and the procedure was repeated 15 times consecutively.

![Fig. 3. Standard deviations of distance measurements taken by the TP in the repeatability test](image)

Graphics in Fig. 3 show the standard deviations of values obtained for $d$ and $D$. Deviations were very low ($\sigma(d) < 1.1 \mu m$) for step-step distances, what in turn means a high repeatability independently of the position.
within DOF. On the contrary, distances step-datum show deviations which increase significantly as the step analysed is farther from the datum. Since this analysis was performed by a TP, the influence of DOF may be discarded. The studies carried out showed the relationship of this tendency with the distance between steps in the X-axis of the MC. Actually, it is a problem derived from the algorithm used by PC-DMIS for the calculation of distances between planes. This algorithm calculates the distance between a surface and a datum by projecting the vector $\vec{c}$ between centroids (C1 and C2) of both surfaces on a vector $\vec{n}$ perpendicular to the first (Fig. 4a). Since vector $\vec{n}$ is determined from the points scanned on the surface, the direction of this vector may change slightly in each test which will affect significantly to the magnitude of the distance calculated. This effect will be greater as the surfaces are farther in X-axis.

![Fig. 4. Calculation of 3D distance between two planes: (a) by PC-DMIS; (b) by projection on one alignment direction.](image)

In order to minimize this effect, it was decided to calculate distance between steps as the projection of vector $\vec{c}$ on a direction $\vec{a}$ perpendicular to the alignment plane defined by S1 and S2 (Fig. 4b). Figure 3 shows the standard deviations of distances $d_a$ and $D_a$ measured this way. As it can be seen, the values of $\sigma(d_a)$ and $\sigma(d)$ are similar each other, regardless the location within DOF in which they were analysed. Nevertheless, the values of $\sigma(D_a)$ are substantially reduced with respect to $\sigma(D)$ down to values lower than 1.5 μm.

This calculation method will be used to compare distances between the CH and TP sensors by using the following expressions:

$$X_a = |d_a^{CH} - d_a^{TP}|$$

$$X_d = |D_a^{CH} - D_a^{TP}|$$

(1)

(2)

where $d_a^{TP}$ and $d_a^{CH}$ are step-step distances and $D_a^{TP}$ and $D_a^{CH}$ are step-datum distances for the TP and CH sensors, respectively. Since distances measured by the TP sensor are not affected by the steps location within the DOF, deviations $X_d$ and $X_a$ show the influence of each step position within the DOF for the CH sensor. High values of these indicators mean a lack of coincidence between both sensors, whereas low values mean higher coincidence. Since each measurement trial was repeated 30 times, the average value of the indicators ($\bar{X}_d$, $\bar{X}_a$) and their standard deviations ($\sigma_d$, $\sigma_a$) were analysed.

The values of the indicators $\bar{X}_d$, $\bar{X}_a$ and their standard deviations $\sigma_d$, $\sigma_a$ for the two digitizing strategies (Z_const and Z_var) are represented in Fig. 5.

Regarding the indicator $\bar{X}_d$ it can be noticed that results obtained are very similar in both strategies with most values below 2 μm and high repeatability ($\sigma_d < 0.5$ μm).
Fig. 5. Indicators ($\bar{X}_δ$, $\bar{X}_δ$) and their standard deviations ($σ_δ$, $σ_δ$) calculated for both digitizing strategies ($Z_{\text{const}}$ and $Z_{\text{var}}$).

On the contrary, values of the indicator $\bar{X}_δ$ are dissimilar between both strategies. When using the $Z_{\text{const}}$ strategy the values of $\bar{X}_δ$ increase as distance step-datum is greater. This reveals that discrepancy between the CH and TP becomes greater as the magnitude of distances measured within DOF increase. However, in the $Z_{\text{var}}$ strategy an important reduction of this effect is observed. In both strategies the variability of measurements $σ_δ$ are similar each other.

The values of $σ_δ$ are higher than $σ_δ$ mainly for the farthest steps from the datum, where values slightly over 1 μm are met. Therefore the indicator $\bar{X}_δ$ has lower repeatability than the indicator $\bar{X}_δ$.

5. Conclusions

The present work analyses how the measurements taken by a CH sensor integrated in a MC are influenced by the location of the digitized surface within DOF. With this aim, several experiments were conducted on an AISI 316 stepped specimen whose flat surfaces were machined by wire EDM.

The measurements were performed under two different strategies. In the first ($Z_{\text{const}}$), the height position of the sensor was kept constant along the scanning of all the steps so that each step was located at different heights within DOF. In the second strategy ($Z_{\text{var}}$), the height position of the sensor was modified for each step so that the digitizing distance was identical within DOF in all of them and coincident with the stand-off. The CH sensor parameters were adjusted in all the tests to ($F_{2000}$, $P_{15}$) in order to meet an optimal acquisition signal (SNR > 50% and $1200 < \text{Total} < 16000$).

The analysis of results was carried out by calculating the discrepancies between the measurements taken by the CH sensor with respect to those obtained by a TP also installed in the MC. According to this analysis, several conclusions can be highlighted:

- When distances of short nominal value ($\leq 4$ mm for a lens of 50 mm focal length) were measured using a $Z_{\text{const}}$ strategy, no significant influence of surfaces location within DOF was observed since similar discrepancies with
respect to the TP were met for all the steps. On the other hand, identical discrepancies were obtained when using a $Z_{\text{var}}$ strategy, what it proves that DOF has no influence in this case.

- As greater distances are measured using $Z_{\text{const}}$, discrepancies with regard to the TP increase. However, discrepancies when using $Z_{\text{var}}$ were similar each other. Therefore, influence of DOF can be minimized by means of $Z_{\text{var}}$ strategy.

- Consequently, the following recommendations can be suggested when using a CH sensor for digitizing:
  - Optimal results could be achieved when distance between the CH sensor and the surface can be kept constant along the digitizing process, preferably at stand-off distance.
  - When it is not possible to adapt the distance between the sensor and the surface during the scanning pass, good results shall be obtained when all the points acquired are distributed around the stand-off in a narrower band than the DOF. In the case of the CH sensor used in this work with a lens of 50 mm focal length, the DOF is 8 mm and the band would be of ±2 mm.

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