Information Efficient White-Light Interferometry

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White light interferometry (WLI) is a precise and versatile tool to measure rough and smooth surfaces. However, it requires a big amount of raw data. Increasing demands on measurement speed and camera resolution urge us to reduce the necessary number of camera frames. We present three possible solutions to increase the information efficiency.

1 Basic principle

A white-light interferometer (for example Coherence radar [1]) measures surfaces by scanning the temporal coherence function of the broadband light reflected from the surface under test. For each object point, we record a correlogram. From the maximum of the correlogram the position of the corresponding object point along the z-axis can be found.

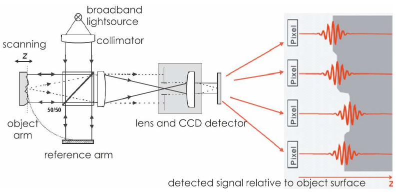

Fig.1 WLI measuring principle.

2 Standard evaluation

The standard solution to find the maximum is the full reconstruction of the modulation of the correlogram. The envelope is reconstructed then from the modulation. This quickly leads to the physical limit given by Shannon's Sampling Theorem. The minimum number of acquired camera frames is:

$$N_{\text{standard}} = \frac{4\Delta z}{\lambda},$$

where Δz is the measurement range and λ is the wavelength of the used lightsource. For further comparison, we define information efficiency as:

$$\eta = \frac{1}{\text{number of acquired raw images}}.$$

For example, we need for measurement range of Δz =100µm and for a wavelength of λ =800nm at least 500 camera frames. Therefore, the efficiency is only $\eta_{\text{standard}} = 0.2\%$.

3 Under-sampling

The knowledge of the spectrum of the lightsource allows under-sampling. The Sampling Theorem for bandlimited signals [2] offers high reduction of the acquired images, but at the cost of the need for a much more accurate sampling. The practical limit is 10x undersampling, thus increasing the efficiency to $\eta_{\text{under-sampling}} = 2\%$.

4 New strategy: Quadrature demodulation

We present a new measurement strategy based on a direct reconstruction of the envelope of the correlogram. The modulation is not reconstructed, because this is not necessary to measure rough surfaces. Using the Hilbert transformation *H* the real signal (correlogram) *c*(*z*) is transformed into the complex signal *C*(*z*)

$$C(z) = c(z) + iH\{c(z)\} = E(z)e^{i\varphi(z)},$$

where *E*(*z*) is the envelope of the correlogram. The envelope can be calculated:

$$E(z) = \sqrt{[c(z)]^2 + [iH\{c(z)\}]^2}.$$

The Hilbert transformation is comparable to a 90° phase-shift-function:

$$E(z) \approx \sqrt{[c(z)]^2 + [c(z+90°)]^2}.$$

We introduce a measurement strategy, where both Re{C(z)} and Im{C(z)} are measured. One point of *E*(*z*) is acquired from two exposures, shifted by 90° (Fig.2).

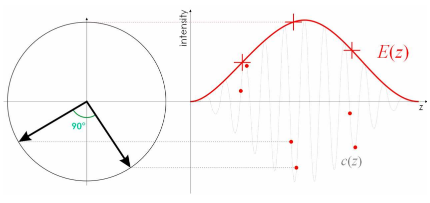

Fig.2 Direct envelope reconstruction.

The standard solution to find the maximum is Three-point-Gauss-interpolation. We only need three envelope points and therefore only six camera frames. For practical reasons, we use 5 envelope points and the resulting information efficiency is for our example described above $\eta_{\text{envelope}} = 10\%$!

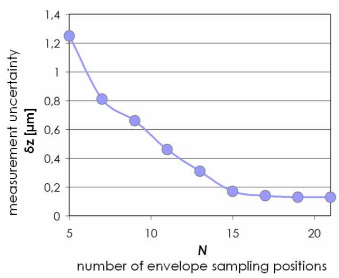

Fig.3 Measurement uncertainty vs. the number of acquired camera frames for a smooth surface and a measurement range Δz =100µm and wavelength λ =800nm.

For the measurement range of 100µm, the achievable measurement urcetainty for 5 sampling positions (10 camera frames) is $\delta z = 1\mu m$.

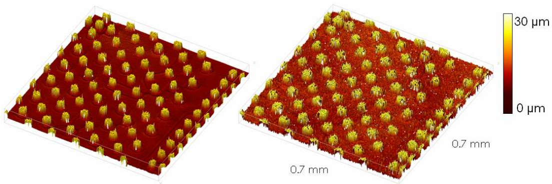

Fig.4 Measurement of ball-grid array. Left: Properly sampled (500 frames), right: Direct envelope reconstruction (10 frames).

5 Adapted Illumination

Another solution to increase the information efficiency is to adapt the object Illumination. Adaptation means to adjust the direction of the incoming rays perpendicular to the surface [3]. One example is the measurement of an inner-conical surface (Fig.5).

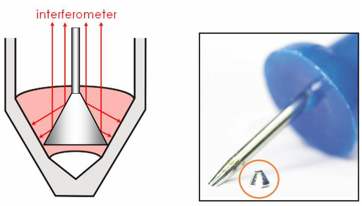

Fig.5 Left: Measurement of an inner-conical surface of an injection nozzle, right: Used 60° micro-conical mirror (Ø1.6mm).

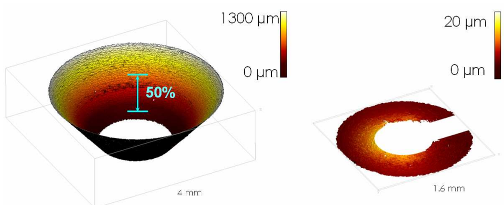

Fig.6 Left: Standard measurement (4000 frames), right: Adapted illumination via conical mirror (120 frames).

6 Adapted reference arm

The ultimate solution to reduce the number of acquired raw data is to put a master object with a comparable surface profile in the reference arm. This offers very efficient quantitative comparison, because we are detecting only relative differences between the master and the measured object.

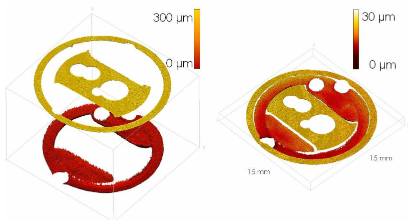

Fig.7 Part of injection system for engines. Left: Standard measurement (1900 camera frames), right: Adapted reference arm (190 camera frames).

7 Summary

Table 1 shows the comparison of the presented evaluation methods for a measurement range of 100µm and wavelength 800nm.

Evaluation according to sampling theorem	$\eta_{\text{standard}} = 0.2\%$	$\delta z = 0.2\mu m$
Undersampling	$\eta_{\text{under-sampling}} = 2\%$	$\delta z = 0.5\mu m$
Quadrature demodulation:	$\eta_{\text{envelope}} = 10\%$	$\delta z = 1\mu m$

Tab. 1 *Information efficiency/comparison.*

Quadrature demodulation displays 50x higher information efficiency without necessity of extremely precise sampling, which is required by under-sampling methods. We cannot quantitatively define the efficiency of the measurement with adapted illumination or reference arm, because the result is always dependent on the shape of the measured object. Table 2 summarizes only the efficiency for the presented examples.

Adapted illumination	$\eta_{\text{standard}} = 0.005\%$	$\eta_{\text{adapted}} = 0.5\%$
Adapted reference arm	$\eta_{\text{standard}} = 0.33\%$	$\eta_{\text{adapted}} = 3.3\%$

Tab. 2 *Inf. eff for adapted illumination and reference.*

References

[1] T. Dresel, G. Häusler, H. Venzke; „Three-dimensional sensing of rough surfaces by coherence radar", Appl.Opt., Vol. 31, no. 7, 919-925, 1992

[2] P. deGroot, L. Deck, "Three-Dimensional imaging by sub-Nyquist sampling of white-light interferograms", Opt. Letters. Vol. 18, No. 17, (1993)

[3] A. Albertazzi G. Jr., A. Dal Pont; "Fast coherence scanning interferometry for smooth, rough and spherical surfaces", Fringe 2005, 605-612, 2005)