Special Properties of Coherence Scanning Interferometers for large Measurement Volumes

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Abstract. In contrast to many other optical methods the uncertainty of Coherence Scanning Interferometer (CSI) in vertical direction is independent from the field of view. Therefore CSIs are ideal instruments for measuring 3D-profiles of larger areas (36x28mm², e.g.) with high precision. This is of advantage for the determination of form parameters like flatness, parallelism and steps heights within a short time. In addition, using a telecentric beam path allows measurements of deep lying surfaces (<70mm) and the determination of form parameters with large step-heights. The lateral and spatial resolution, however, are reduced. In this presentation different metrological characteristics together with their potential errors are analyzed for large-scale measuring CSIs. Therefore these instruments are ideal tools in quality control for the practical use in industry and for standardization are discussed by examples of workpieces of automotive suppliers or from the steel industry.

1. Introduction
Today increasing demands on the functionality of surfaces require precise measurements in the quality control or in R&D with high performance. The demand for ambiguous functionalities of surfaces leads to the compliance of small tolerances. Even tool-marks remaining from the manufacturing process can reduce the function and therefore the surface of the parts must be tested. So for static sealing surfaces, e.g. the flatness is important for the functionality. In other cases two surfaces must be parallel or step heights be manufactured in a very accurate and reproducible way for fittings, e.g. In many cases line profiles of traditionally used tactile systems are not sufficient anymore, because the complete area must be taken into account. On the other hand optical measurement methods deliver fast and reproducible results. A large field of view without time consuming stitching, however, is required for a fast characterisation of a complete area. Therefore coherent scanning interferometers (CSI) –also known as white light interferometers- are an ideal tool, because the performance in z-direction is independent from the field of view [1]. With these instruments 3D-profiles of larger areas (30x30mm², e.g.) can be determined with high precision. In contrast to microscopic set-ups the telecentric beampaths used in large area CSIs allow also measurements of deep lying surfaces without shadowing. The lateral resolution, however, of such a set-up, is reduced. This paper should highlight the chances of optical metrology systems especially for large volumes, but also comparability of the measurements. In the following section facets of practise with CSI are covered based on the experience of users in quality inspection.

2. Coherent Scanning Interferometers for large measurement volumes

2.1. Lateral and spatial resolution of Coherent Scanning Interferometer with telecentric beampath

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The most common CSIs use a microscopic set-up. Here the field of view is comparable small and due to the working distance and shadowing effects the characterisation of deep lying surfaces within bore-holes, e.g. is not possible. This is overcome by a set-up with a telecentric beam path with a large field of view. This is typically realized by a Michelson or a Twyman-Green interferometer [2]. In the following investigations a commercially available instrument (TMS-100 TopMap Metro.Lab of Polytec) was used. A measured 3D-profile as an example for the characterisation of a deep laying surface is shown in Figure 1, where the lower surface is 40 mm below the upper surface. As it can be seen the characterised surface is not flat and toolmarks can clearly be identified. Today parallelism of two surfaces, step-heights with a distance of up to 70mm, e.g., or flatness are measured routinely in quality inspection of automotive parts, e.g.

Figure 1. Deep laying surface, the diameter of the work-piece is 19 mm, the lower surface is 40mm below the upper surface

The low aperture of a telecentric set-up, however leads to a lateral resolution, which is poorer as in microscopic systems: According to the Raleigh criteria the resolution R is given by

\[
R = \frac{0.61 \times \lambda}{NA}
\]  

(1)

Here \( \lambda \) indicates the central wavelength and NA the numerical aperture. Referred to (1) the optical resolution for a telecentric set-up for a field of view of about 30x30mm\(^2\) is about 39\(\mu\)m -compared to an optical resolution of a microscopic system with a 50x objective, which is about 1\(\mu\)m. The different results of measurements with a telecentric and a microscopic set-up is demonstrated by Fehler! Verweisquelle konnte nicht gefunden werden. These pictures show 3D-profiles of a nebulizer part: On the left-hand side a result is shown obtained with the telecentric set-up of the CSI: Form parameter like flatness, radius or step height can be determined, but small nebulizer holes within the membrane are not resolved. In the 3D profile on the right hand side of Fehler! Verweisquelle konnte nicht gefunden werden. determined with the microscopic set-up the small holes and the material throw-out caused by the manufacturing process can clearly be identified.

Figure 2. 3D-Profiles of a large area measurement (left side) and microscopic field of view (right side) from the center
The limitation of the optical resolution of CSIs with a telecentric beampath works like an intrinsic low-pass filter. The optical resolution, calculated from the diffraction limit, should not be mixed up with the lateral resolution: Up to now no generally accepted definition exists for the lateral resolution. A possibility is determination by an appropriate standard: We used a depths measurement standard with calibrated rectangular grooves of 90 nm depth and different lattice constants. The rectangularity has advantages for the rectangular adjustment of the standard to the z-axis. The Figure 3 shows the line profile from a measurement with a large area CLI (optical resolution according the Raleigh criteria: 40µm) on a rectangular grating (lattice constant: 800µm, depth: 80 nm). The used instrument has a pixel diameter of 40µm, the same as the calculated optical resolution. At the edges the artefact of so-called batwings can be identified. The batwing effect is caused by superimposition of the interference component of the reference wave and the light reflected or diffracted from the higher surface level on the one hand and the interference between the reference wave and the light propagating back from the lower surface level on the other hand [3]. Because such artefacts lead to wrong values of most GPS-parameter and S-filter has to be applied.

**Figure 3.** Extracted line profile (original data) of a rectangular grating with a grating constant of 800µm and a depth of 80nm

The part of the grating with smaller lattice constants, however, cannot be resolved completely: The Figure 4 shows the measurement result for the height transfer function for gratings with 5 different lattice constants. A more detailed description can be found in [4], e.g.

**Figure 4.** Transfer characteristic of the investigated interferometer with telecentric set-up, when the measurement data is digitally filtered.
From the result shown in Figure 4 a cut-off wavelength of about 250 µm is determined by the 3 dB point. In Figure 5 a measurement is shown on a rectangular grating with a depth of 80 nm and a lattice constant of 80 µm, which is twice of the pixel diameter. Therefore the Nyquist Shannon theorem is violated [5]. It is obvious, that the measured profile does not correspond to the real surface structure. So in the case of structures less than twice or even more of the pixel resolution the transfer function according to [6] cannot be defined correctly. Therefore it is also obvious, that roughness parameter with shorter wavelengths than at least twice the pixel resolution cannot be determined with a comparable result to tactile systems with a 5 µm radius of the tip, e.g.

![Figure 5](image.png)

**Figure 5.** Artefacts appear if a lattice with 80 µm grating constant is measured with a corresponding pixel diameter of 40 µm without filtering

So the spatial resolution is worse than the optical resolution and in order to obtain no artefacts S-filter and low-pass filter have to be applied. The VDI/VDE 2566 part 1.1 guideline indicates as a rule of thumb, that the wavelength of the full modulation depth determined by the 3dB point, is in practice 4 to 6 times greater than the calculated optical resolution [7]. Determined by the 50% modulation depth it is 2-3 times greater. Other authors suppose amplitude decay to 70% for sine structures and 90% for rectangular structures [8]. Although all this is important for the comparability of different instruments and methods the description by common international standards is quite poor, how a user should do this filtering in practise. A detailed description of possible errors in CSI instruments is given by Gao et al. [9], who compared microscopic instruments of three suppliers; the VDI/VDE 2566 part 1.3 guideline [10] will also cover telecentric set-ups.

2.2 **Special requirements for Coherent Scanning Interferometers with telecentric beampath for the Determination of form parameters**

When measuring parameters like flatness, waviness, parallelism results are not affected by the filtering, because here low-pass filter have to be applied anyhow. Step-height determinations are also possible. The evaluation algorithms even for simple flatness measurements, however, are also not standardized: In practise, e.g. a simple spike within the 3D-profile disturbs a flatness measurement. With an a-priory assumption, that a single spike cannot occur, a filter has to be applied to the raw data of a 3D-profile eliminating this spike. By the previously described filtering most of simple spikes are eliminated anyhow. At the moment there is no standard rule, which filter and which parameter an unacquainted user should utilize in the day to day practise: It can be a simple low-pass filter or a median filter with a certain threshold, to name only a few possibilities. The new public-funded German OptAssyst project of research institutes, metrology equipment suppliers and users mainly from the automotive industries works on a user-oriented assistance systems for the reliable use of interferometric and confocal distance sensors in the industrial production.
The fast measurement time of a few seconds make CSIs to an ideal tool for quality control of these parameters, for samples or even for a 100% inspection in the manufacturing line. The need to analyze the complete surface is obvious by the following example: The Figure 6 shows the picture of a sealing surface, on which the outer and inner annular surfaces should be controlled; Taking the complete areas into account the result for flatness is 2.53μm (central picture), whereas two line profiles lead to a result of 1.2μm and 1.6μm, resp., because some of “higher” parts are not hit by the lines.

![Sealing work-piece, left side: original picture of the work-piece, centre: 3D-profile with the flatness determination, right side: 2 line profiles of the work-piece, location of the line profiles are indicated with dotted lines in the 3D-profile](image)

**Figure 6.** Sealing work-piece, left side: original picture of the work-piece, centre: 3D-profile with the flatness determination, right side: 2 line profiles of the work-piece, location of the line profiles are indicated with dotted lines in the 3D-profile

Another example, where it is very hard to obtain repeatable and reproducible results is shown in Figure 9. The cross section in the picture on the left side shows, that the inner area has the form of a truncated cone. The picture on the right side shows the waviness of a circular-profile of the inner ring. For this part the process capability for quality inspection was not achieved by tactile systems in contrast to the results obtained by CSI-instruments.

![3D- and line profiles of a shock-absorber part with a diameter of 35mm](image)

**Figure 7.** 3D- and line profiles of a shock-absorber part with a diameter of 35mm

In addition measurement time is an important issue for routine measurements in quality control: An example for in-line measurements of piezo fuel injector for car engines is shown in Figure 9. The vibrations -measured with Laser Doppler Vibrometry- caused by the manufacturing machines are shown on the left side. These vibrations must be suppressed and after that the measured 3D-profile shown on the right side can be obtained.
The complete cycle for one part includes the loading, the settling down of the vibrations after loading (see Figure 8) the automatic finding of the areas of interest, the measurement calculation, export of the result to the data base and unloading. The cycle time is about 6 s. Within this special environment tolerances of flatness and parallelism of about 1 µm can be checked, which means reproducibility and repeatability must be less than 100 nm. Unfortunately only few suppliers specify uncertainties of flatness and step-height measurements. Usually only resolution values are given. In most cases this is not very helpful for typical tasks, because here only the minimum resolvable step-height difference is described. In addition, in many cases a statistical value of multiple measurements is published, leading to resolution specifications in the sub-nanometer region. The reason for that might be, that no common rule exists, how to specify flatness or step height measurements for a CSI instrument. We suggest a procedure with a step height artefact measured in the same way as it is done for repeatability and reproducibility determinations in the industry. These specification data, however, give only a first indication, because the real measurement uncertainty depends on the geometry of the sample and the environment. For some workpieces a large z-range is needed to perform the measurement. A higher scan-range can only be covered with a motorized linear stage instead of the more commonly used piezo stage in most CSIs. Motorized linear stages can exhibit relevant positioning errors. Therefore the z-scale of such large-scale CSIs has to be calibrated. As the positioning errors are reproducible they can be calibrated by the help of a correction table [11]. The uncertainty in the vertical direction can be significantly reduced by this calibration procedure. A first analysis of the long-term behaviour of the stages positioning errors by trend shows a good stability. However, the absolute measurement - error is similar also for smaller step heights and therefore an uncertainty value in percent of the step-height is not suitable.
2.3 Using “roughness parameter” calculated from measurements with CSIs for bending classification

Even calculating $S_a$ or $S_q$ roughness parameter in the “traditional way”, due to the intrinsic low-path filter caused by the spatial resolution, leads automatically to a waviness window parameter ($W_{at(1-5)}$ or $W_{ca}$): The window-parameter $W_{at(1mm-15mm)}$ allows an accurate classification of critical bending radius (see fig.10).

| Sample | $S_a$ (µm) | $S_q$ (µm) |
|--------|------------|------------|
| 1      | 8.38       | 9.82       |
| 2      | 8.66       | 10.27      |
| 3      | 7.67       | 9.09       |
| 4      | 9.33       | 11.76      |
| 5      | 12.48      | 16.61      |
| 6      | 10.23      | 12.53      |
| 7      | 7.89       | 9.81       |
| 8      | 7.83       | 9.28       |
| 9      | 8.37       | 9.94       |

**Figure 10.** 3D-profile of nine aluminium bending probes and the $S_a$ and $S_q$ values (from left to right)

This allows the qualification of the probes in respect to their bending behaviour. The Figure 11 shows the correlation between the bending radius versus $S_a$ and $S_q$.

**Figure 11.** Roughness v.s. bending radius of aluminium (courtesy of W. Hotz, Novelis AG, Sierre (CH))

3. Conclusion

It was shown, that large area measuring CSI is a useful tool for the determination of flatness, parallism and step-heights and in addition surface parameters can be used to determine material properties with high repeatability and reproducibility. Compared to common tactile systems the complete area can be characterized within a short time and therefore ideal for (automated) quality inspection.
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