THE DIFFRAXICON-INTEROMETER FOR CYLINDER TESTS

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Abstract: The shape measurement of technical cylinder mantle surfaces requires special measures to obtain a spatially low frequency interferogram indicating the shape deviations from an ideal cylinder surface. For this purpose the use of diffraxicons is proposed and demonstrated. The surface roughness is sufficiently eliminated by grazing incidence interferometry for high quality surfaces becoming more and more essential for high accuracy applications as e.g. in the nano-technology and modern lithography.

Keywords: Interferometry, Computer-generated holograms, Interferometric Cylinder Test

1 INTRODUCTION

Precision engineering relies heavily on the use of turned and milled cylindrical surfaces. Since the precision requirements are increasing due to automation of the production and the miniaturization of the mechanical parts there is an increasing need for higher and higher measurement accuracy. Beside this increasing demand for higher accuracy there is also a strong demand for:

- Enhanced measuring speed and
- Reliable elimination of adjustment aberrations from the measurement results.

Historically, the mechanical measuring machines or coordinate measuring devices are the established means to obtain roundness data [1]. But in all these measuring processes the sample under test has to be placed within the frame of the measuring device. In the case of mechanical stylus measurements involved procedures are necessary to get rid off the positional deviations of the test sample within the frame of the measuring machine. In addition the mechanical scanning with the help of a stylus is rather time-consuming which makes the whole measuring process prone to drifts resulting in distorted data sets.

The replacement of the stylus through an optical focal plane indicator provides a non-contact measurement facility but does not improve the drift behavior. Only the direct comparison of the surface with a reference normal provides a new quality of the test concerning accuracy, speed and the elegance for the elimination of adjustment contributions.

Additionally, technical surfaces are rough on the scale of the wavelength used. Therefore, common interferometers are not suited for the measurement of the global shape of such surfaces. To overcome the micro-structure of the surface the wavelength has to be increased which can be done either by the use of IR-wavelengths or/and the use of grazing incidence onto the surface under test. In the latter case the wavelength is transformed into an effective wavelength of $\lambda/\cos\vartheta$. If the incidence angle is close to 90° the effective wavelength becomes rather large and enables the shape measurement of rather rough surfaces. As a rule of thumb the effective wavelength should be 10-times the rms-roughness of the surface under test.

In this publication we want to describe a method for the interferometric measurement of cylindrical mantle surfaces in grazing incidence where the beam splitting and shaping is done by means of diffractive optical elements which shall be called **diffraxicons** (**diffr**active **axicons**). Diffraxicons are computer-generated holograms (CGH) which generate a set of conical wavefronts if they are illuminated e.g. by a plane wavefront.

2 INTERFEROMETRIC PRINCIPLE

The principle of interferometry is based on the coherent[§] superposition of two wavefronts where one wavefront passes the object surface and the other is used as a reference. To make the principle more clear to the reader let us discuss normal surface measuring interferometry working with reflection of a wavefront off a plane object and a plane reference surface. For the demonstration let us

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[§] it means that two wavefronts are superimposed which are generated by division of one wavefront.

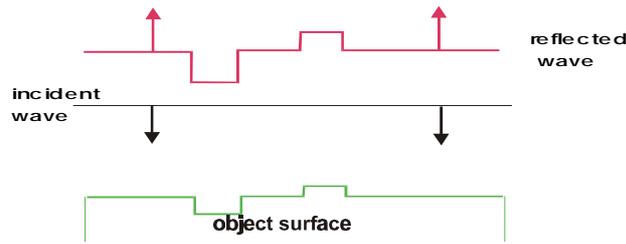assume a plane surface with a step profile.

Figure 1. Transfer of the object structure onto an impinging plane wavefront via reflection

As can be inferred from Fig. 1 the surface profile of the object is transferred onto an impinging plane wavefront due to the time delay of the wavefront reflected off the surface structure to be tested. The wavefront deformation can be made measurable by superimposing a plane reference wavefront forming a two-beam interference pattern. The cosine-type intensity distribution of the interference pattern can be evaluated for the phase which represents in the discussed example the surface deviations from a plane surface. If the reference wavefront is tilted with respect to the object wave it is possible to obtain a straight fringe pattern (see Fig. 2).
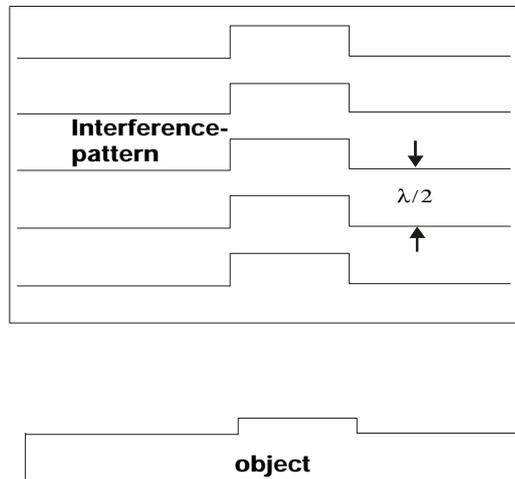

Figure 2. Interference pattern with a tilted reference wavefront for an object having a step structure. Due to the reflected light geometry the optical path difference is doubled due to the double pass to and fro of the object surface.

The interference fringes are curves of e.g. equal minimum intensity[&] which follow in periodic succession indicating an increase of the air gap in a Fizeau interferometer of half a wavelength. By measuring the fringe shift in the interferogram the object deviation can be obtained. In the chosen example one fringe for He-Ne-laser illumination (633 nm) results in an object deviation of 316 nm. We close here this simple illustration of the interferometric mapping of surface profiles with the help of interferometry. Today the measurement is fully automated [2]. For this purpose the interferometers are equipped with photoelectric CCD-arrays and piezo-electric transducers to shift one of the interferometer mirrors in order to obtain different intensity patterns of the same object scene which is necessary to extract the phase information from the intensity pattern.

3 GRATINGS RESP. COMPUTER-GENERATED HOLOGRAMS AS BEAM SPLITTERS

After the short introduction to the interferometric principle the special problems of the tests of technical or rough surfaces shall be dealt with. The mantle of a technical surface can be characterized in the micro-region by the roughness parameters and in the global sense by shape parameters. Here we are mainly interested in the shape parameters, i. e., for the cylindrical mantle surfaces the deviations of the real surface from an ideal mathematical representation of the surface to be tested. To

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[&] Interference enables the cancellation of light with light resulting in a minimum of intensity.

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get an access to the shape parameters one has to quench the influence of the roughness onto the interference pattern. We discuss here the case of grazing incidence interferometry. Grazing incidence means an increase of the effective wavelength from λ to $\lambda/\cos\vartheta$ with ϑ being in the neighborhood of 90°. As a first simple arrangement using CGH´s the case of planeness testing will be discussed. In this very case the CGH´s degenerate to simple gratings resulting in the arrangement due to Fig.3.
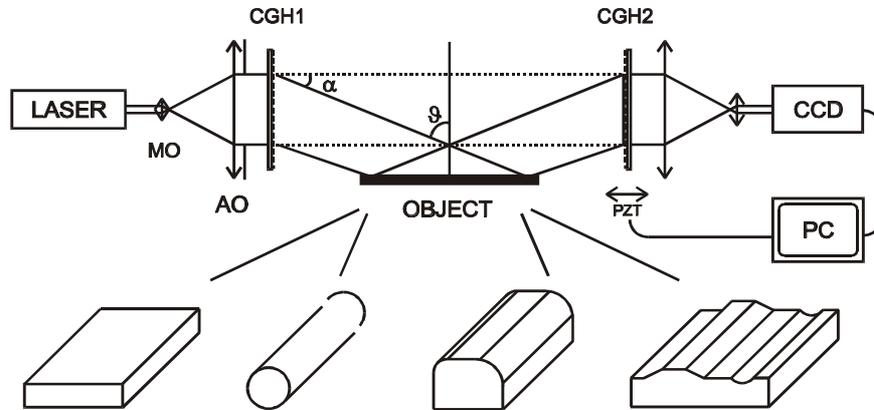

Figure 3. Scheme of the interferometer for technical surfaces using diffractive beam splitters (CGH$_{1,2}$[&]) for different rod shaped objects: plane surface, cylinder, mathematically convex rod object, general rod object (in the order from left to right). The CGH´s have to be adapted to the meridian curve of the rod shapes.

The light of a laser (e.g. a red He-Ne-Laser or of a semiconductor laser) is expanded and very exact collimated to a plane wavefront by means of a micro-objective, a pinhole, and a well corrected astro-objective. This plane wavefront enters the interferometer consisting of two identical CGH´s – CGH$_1$ and CGH$_2$. The first CGH splits the wavefront into a set of wavefronts. Here only two diffraction orders are of interest, i.e., the zero order plane wavefront and the plus first wavefront whose shape is determined by the CGH-structure. In the simplest case of a grating this wavefront is also plane. The first order wave is reflected from the surface to be tested and impinges onto the second CGH where it is again diffracted. From the set of diffracted wavefronts only the nearly plane wavefronts propagating along the optical axis are allowed to interfere on the detector array. The imaging of the object surface is carried out by a telescopic optical system in front of the CCD-detector. The resulting intensity is detected, digitally grabbed, and read into the memory of a PC. For the purpose of the so-called phase shifting evaluation of the interference pattern the second CGH is mounted on a stage which can be axially shifted via a PZT-device providing several phase shifted intensity patterns for the determination of the phase[§].

The function of the diffractive beam splitters or CGH´s can easily be understood at the example of the planeness test where the CGH´s degenerate to simple gratings. It is well known /3/ that gratings disperse an incoming plane wavefront into a set of plane waves leaving the grating under different but known angles α_m relative to the grating normal. In the case of perpendicular incidence the following grating equation[%] holds:

$$p \sin \boldsymbol{a}_m = m\boldsymbol{l} \tag{1}$$

where p is the pitch and m is the order number of the diffraction order (m=0; ±1; ±2;...).
For this interferometer based on diffractive beam splitters the following simple equality holds:

[&] CGH is the acronym for computer-generated hologram, in case of plane surfaces the CGH are simple gratings

[§] The two-beam interferometer delivers a cos-type intensity distribution: $I(x,y) = I_0\{1 + V\cos(\Phi - \boldsymbol{j})\}$, where Φ is the wanted object phase and φ is an arbitrary reference phase. The freedom in the choice of this reference phase is exploited in the phase shifting interferometry approach for the extraction of the phase to be measured Φ from several intensity distributions of the same interferometric scene.

[%] The grating equation is the condition for constructive interference under the angle α_m which means that the optical phase difference of interfering beams originating from neighboring periods is a whole number of wavelengths.

$$\sin \boldsymbol{a}_m = \cos \boldsymbol{J}. \tag{2}$$

From these equations (1) and (2) follows a surprisingly simple relation for the effective wavelength:

$$\boldsymbol{l}_{eff} = \boldsymbol{l} / \cos \boldsymbol{J} = p / m. \tag{3}$$

Since we are mainly interested in the first diffraction order we arrive at:

$$\lambda_{eff} = p. \tag{4}$$

With this fundamental equation for interferometry using grazing incidence and gratings in our mind it is rather easy to transfer this relationship to any meridian curve provided the CGH-structure consists of parallel curves to the meridian [4]. A cross section through the center of symmetry will seemingly look identical to the grating case. Since the incoming and the diffracted wavefronts remain in the plane defined by the grating vector and the surface normal which for simplicities reasons is here the plane of drawing the same set of equations holds for arbitrary meridians.

An optimum in light efficiency and fringe visibility in the interference pattern can be obtained if there is a balance between the light of the reference wave – here the zero order- and the light undergoing a reflection at the object and afterwards being diffracted by the second CGH into an on-axis-direction. Provided the reflectivity of the object surface is approximately 100% then the best solution is a balance between the intensities of the zero and ±first orders. This can only be attained by using phase shifting CGH´s. A simple solution is a CGH with a binary groove profile with the aspect ratio ½ and a phase delay[&&] of ca. 105° between the wavelets from the grooves and the ridges. Such structures are known as Ronchi-phase structures.

4   DIFFRAXICONS AS BEAM SPLITTERS AND BEAM SHAPERS FOR CYLINDER MANTLE SURFACES

We shall now concentrate on the measurement of cylindrical surfaces: either the inner mantle surface of a hollow cylinder or the outer surface of a full cylinder or both surfaces if necessary. The CGH´s become in this case the structure of a diffractive axicon which means that the diffracting grooves are equidistant circles with a common center of symmetry. The diffracted waves originating form an incident plane wavefront are conical wavefronts. An overview on the geometry of such an interferometric setup gives Fig. 4.
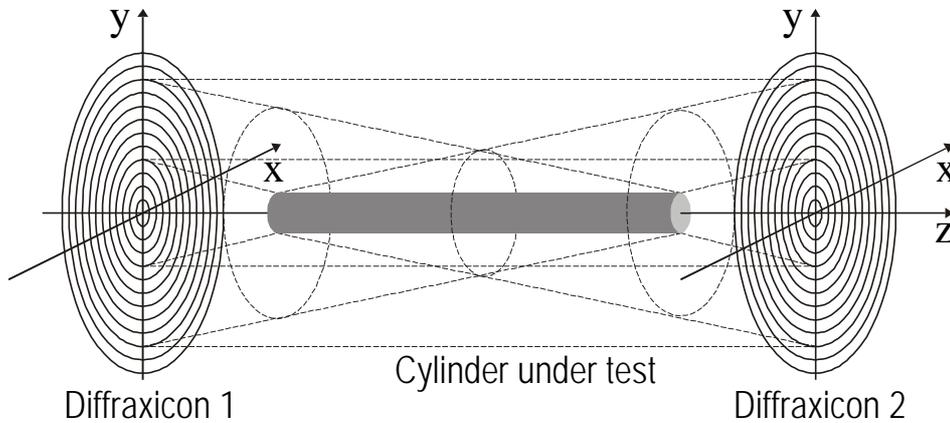

Figure 4.   Scheme of the interferometric setup for testing cylindrical mantle surfaces using two identical diffraxicons (diffractive axicons as CGH´s).

The conical waves impinge radially under an angle ϑ respectively α onto the surface to be measured and are reflected approximately under the same angle in the direction of the second diffraxicon where the zero order reference wave and the reflected wave are recombined via diffraction at the second diffraxicon into an on-axis direction. The center of gravity of the surface under test is sharply imaged onto a detector array which is for the visible region a CCD-camera or for the IR-region a Stirling-cooled PtSi-array. The advantage for the IR region is two-fold: (1) the imminent anamorphic distortion due to grazing incidence is reduced and (2) it is possible to measure the surface shape of rather rough test samples.

[&&] This can be obtained by using the structure depth: $\Delta z = \dfrac{105}{360} \dfrac{\boldsymbol{l}}{(n-1)}$

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Since the interference pattern depends also on the position of the test sample within the frame of the empty interferometer one has to subtract the deviations caused by the positioning of an ideal cylindrical surface. This can be done with sufficient accuracy by using the first term of a Taylor expansion of the surface functional after the adjustment parameters which is for cylindrical surfaces a 4-dimensional fitting problem.

After the adjustment parameters have been determined via a least-squares-fit the relevant deviations of the surface from an ideal cylinder can be displayed. The evaluation is done via phase shifting interferometry either by axially shifting the first or the second diffraxicon.
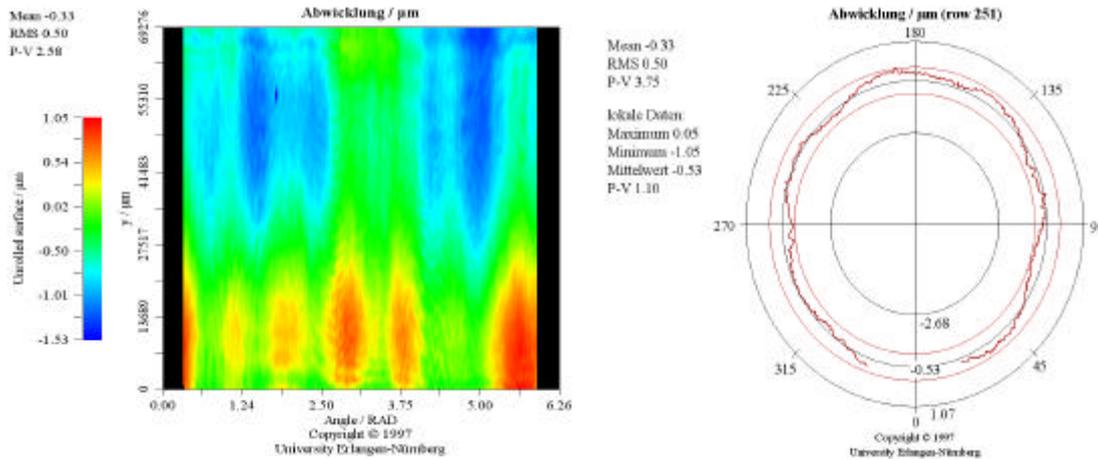
5 MEASURING EXAMPLES

Figure 5. Deviations of the inner mantle surface of a roller bearing cage. On the left side: unrolled surface (vertical direction: length of the cylinder; horizontal: circumference); on the right: display of a single cross section through the deviation picture in radial coordinates. All deviation data are scaled in µm.

As measuring examples the test of the inner surface of a roller bearing cage shall follow (see Fig. 5). In the Fig. 5 the surface deviation of the cylinder is given in two different display forms. The periodic machining traces can be made more obvious if two measurements are subtracted from each other where for the second measurement the cylinder underwent a 180°-rotation (Fig. 6).
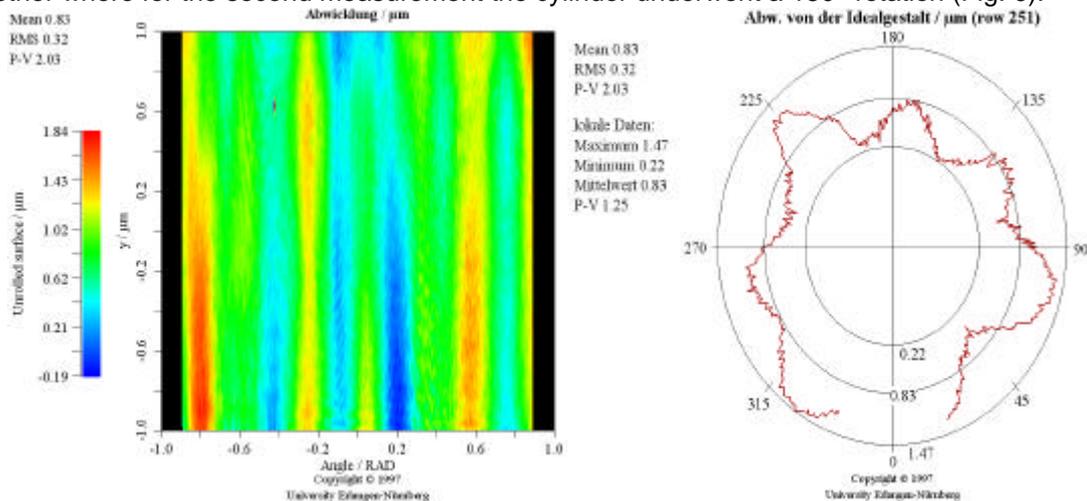

Figure 6. Display of the roundness deviations by eliminating the conical deviation via a difference measurement of the cage in basic and 180°-rotated position. On the left: unrolled surface display with the z-axis in vertical and the circumference in horizontal direction; on the right: Cross section through the deviation pattern in a radial display of the roundness deviations. All deviation data are scaled in µm.

In a last example (Fig. 7) the surface deviations of the outer surface of a cylindrical rod are displayed in a pseudo-3D-plot.
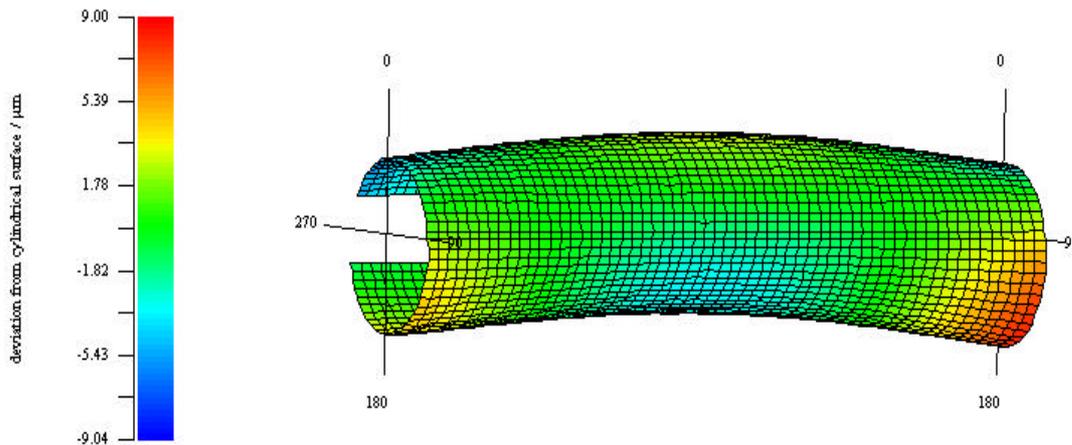
Figure 7. Pseudo-3D-plot of the surface deviations of a cylindrical rod with 6 mm diameter and 150mm length showing mainly bending by about ± 9 µm.

6 SUMMARY

Technical surfaces having a roughness in the µm-region can be measured with the help of grazing incidence interferometry. The use of diffraxicons enables the beam shaping of the probe wavefront for any type of rod surface. The dominant type is of course the cylinder due to the machining on a turning or grinding lathe. It is possible to measure the inner and the outer mantle surface of cylinders also together provided the cylinders are concentric. In the publications summarized in reference [4] other examples have been successfully investigated.

Typical parameters of the interferometric diffraxicon test:

- Diameter: 2....60mm
- Length: 20...300mm
- Scaling: 5µm surface deviation from fringe to fringe
- Max. deviations: ca. 100µm from ideal shape
- Repeatability of single measurement: <0.05µm rms
- Measuring time: <15s
- Display of data: 3D-Plot, unrolled false color display, Polar diagram(roundness)
- Number of measuring points: ca. 300 000 depending on the surface geometry

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