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Spectral Interferometry with Lateral Chromatic Encoding

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Abstract

In this paper, a new single-shot line sensor based on Fourier-domain spectral interferometry is presented. Each point of the sampled line is encoded by a different wavelength obtained by a chromatic dispersion at a grating. The requested height profile of the line is determined by combining a phase detection algorithm with an appropriate model-based approach. The robustness of this algorithm with respect to errors in the initial condition is analyzed before the final presentation of a measurement result.

Introduction

During the last decade, a lot of progress has been achieved in fields like nanotechnology, micro-, and optoelectronics. As a prerequisite for further efforts and high quality manufacturing, these novel technologies create new challenges for modern optical metrology with respect to high-resolution, fast, and sensitive measurements. For realizing accurate height measurements many concepts for single-shot point sensors have been proposed using chromatic confocal or white-light interferometric measurement principles. In order to increase the measurement speed, it is desirable to extend these approaches to line sensors, where the height profile of one line of the object's surface is measured in parallel. For instance, this aim can be achieved by sensors, where the light of a white-light laser source is dispersed chromatically and projected onto one line of the object's surface such that each point on this line is encoded by a certain wavelength. By using the confocal measurement principle, it is then possible to realize a scanning line sensor [1]. There are further propositions for a fast line sampling by combining the lateral chromatic encoding with optical coherence tomography [2, 3], which however require a full-range mechanical scan in the reference arm. Yelin et al. [4] presented a setup, where the height information is obtained by controlling the group delay of a pulsed laser light with a scanning element in the reference arm.

In this work, we present the setup and a model-based signal evaluation for a line sensor without full-range mechanical scan, which uses the same illumination technique combined with Fourier domain spectral interferometry. In the experimental setup, a line with a length of approximately *1mm* is scanned simultaneously with *1000* sampling points.

This paper is organized as follows: Firstly, the measurement principle and an introduction to the experimental setup are presented. Afterwards a model-based signal evaluation is given to extract the desired height profile from the acquired raw data. Finally, the concept is proven by means of some experimental results.

Measurement Principle

The presented sensor is a single-shot line sensor concept based on Fourier domain spectral interferometry, where the height information is encoded in a single spectrometer line. Its schematic is depicted in figure 1. A broadband, fiber coupled light of a super luminescence diode is collimated by two achromatic lenses. The collimated light then passes a beam splitter, where it is split into a reference and an object wave.

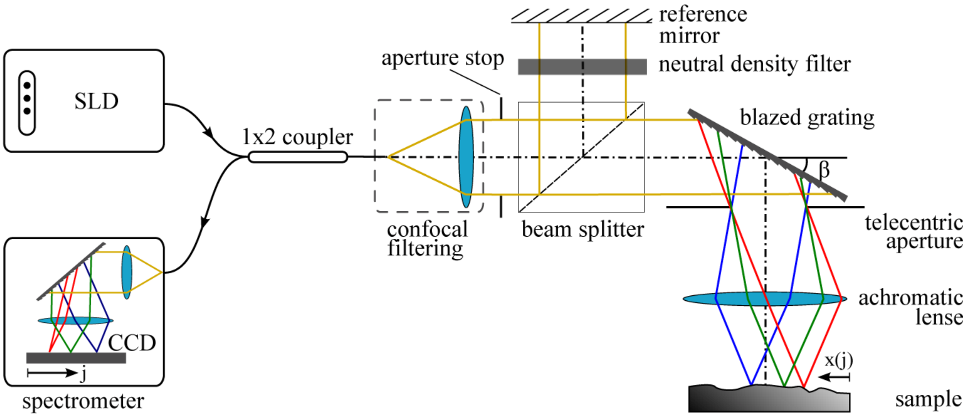

Fig. 1: Schematic of the white-light Michelson-like interferometer with a lateral chromatically dispersed focus, a plane reference and detection in the optical frequency domain utilizing a grating spectrometer.

Light in the object arm is then chromatically dispersed by a grating and focused onto the measurement object by an achromatic objective. Due to the wavelength dependent angle of incidence, the objective forms a focus line in the object space with each wave number k encoding a different lateral position $x(k)$ on the line. An aperture stop in the back focal plane of the objective is used to achieve a telecentric imaging to avoid variations of the lateral position of the individual wavelengths within the measurement volume. The back reflected light from the object passes the grating again and is coupled back into the fiber. A 1x2 single mode fiber coupler and a fiber coupled spectrometer is used to acquire spectrally resolved interference signals. The relation between the pixel *j* on the spectrometer's CCD, its respective wave number *k*, and lateral position *x(k)* on the illuminated line is determined by calibration. The reference arm consists of a neutral density filter for adjusting the intensity and a reference mirror. This arm has a different optical path length in comparison to the object arm to achieve a constant carrier frequency in the spectrally resolved signal.

With respect to the physical modeling of the sensor [5], the desired height information is encoded in the phase *φ(k)* of the acquired intensity signal. After subtracting the phase of a mirror measurement, the unwrapped phase of the interference fringes is

$$\varphi(k) = k \cdot d(k) + 2\pi m \,;\, m \in N, \tag{1}$$

where *m* is a constant, but unknown value. Hence, eq. (1) should be differentiated in order to extract the optical path difference (OPD) *d(k)*:

$$\gamma(k) = \frac{\partial \varphi}{\partial k} = d(k) + k\frac{\partial d}{\partial k} = d(k) + k\,b(k). \tag{2}$$

In contrast to ordinary point-wise white-light interferometry, eq. (2) becomes a differential equation instead of a linear equation, such that an additional signal evaluation has to be added, in order to get the required height profile.

Signal Evaluation

In the signal evaluation process, the course of the OPD *d(k)* for a certain range of wave numbers *k* must be determined based on the differential equation (2). Firstly, the phase *φ(k)* has to be extracted from the registered intensity values by using an ordinary phase detection algorithm. However, depending on the object's surface, this pre-evaluation step must be adapted due to the fact that the phase's sign can change within one measurement [5].

For the line determination, the measured line on the object's surface is divided into *n* discrete sampling points, each illuminated by a different wave number k_j. Monochromatic light of each wave number is afterwards registered by the spectrometer, such that the discrete phase φ_j with $1 \le j \le n$ can be determined. A subset of the whole line is schematically depicted in figure 2, where two exemplary sampling are presented, having OPDs d_j, d_{j+1} and their slope b_j, b_{j+1} with respect to the wave number *k* (see equations (1) and (2)).

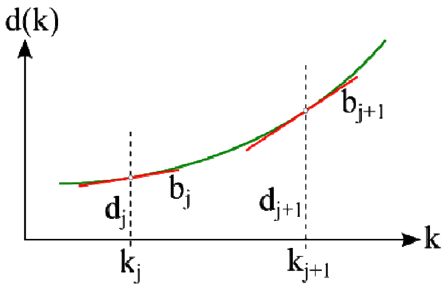

Fig. 2: Schema of a section of the line profile.

By using Taylor's theorem it is possible to determine the two-way relationship between the points (k_j,d_j) and (k_{j+1},d_{j+1}). Hence, the OPD difference between two adjacent sampling points is the mean value of the first order approximations to the OPD:

$$d_{j+1}-d_j=\frac{1}{2}\left(k_{j+1}-k_j\right)\left(b_{j+1}+b_j\right)=\frac{1}{2}\Delta k_j\left(b_{j+1}+b_j\right) \qquad (3)$$

Now, equations (2) and (3) are evaluated at each pixel $j \in [1,n]$ which yields the following system of linear equations:

$$\underbrace{\begin{bmatrix} k_1 & 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \\ 0 & k_2 & \ddots & \vdots & 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 & \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & k_n & 0 & \cdots & 0 & 1 \\ \Delta k_1 & \Delta k_1 & 0 & 0 & 2 & -2 & 0 & 0 \\ 0 & \ddots & \ddots & 0 & 0 & \ddots & \ddots & 0 \\ 0 & 0 & \Delta k_{n-1} & \Delta k_{n-1} & 0 & 0 & 2 & -2 \end{bmatrix}}_{A} \cdot \underbrace{\begin{bmatrix} b_1 \\ \vdots \\ b_n \\ d_1 \\ \vdots \\ d_n \end{bmatrix}}_{\begin{bmatrix} B \\ D \end{bmatrix}} = \begin{bmatrix} \gamma_1 \\ \vdots \\ \gamma_n \\ 0 \\ \vdots \\ 0 \end{bmatrix} \qquad (4)$$

Since A is a $(n\text{-}1) \times (n)$-matrix, the system of linear equations has got one DOF and hence, the solution vector $X = [B\ ,\ D]^T$, obtained by a common linear solver, lies within a one-dimensional vector-plane:

$$X=\begin{pmatrix} B \\ D \end{pmatrix}=\begin{pmatrix} B \\ D \end{pmatrix}_1+\tau\cdot\begin{pmatrix} B \\ D \end{pmatrix}_2 \quad ; \quad \tau\in\Re^1 \qquad (5)$$

The parameter τ in eq. (5), and hence the effective solution of the height profile is only obtainable with a certain a priori information of the course of the object's surface [5]. Due to the linear relationship between every sampling point, this information can be reduced to the knowledge of the OPD d_1 of the first illuminated point on the line.

Now, it is assumed, that the initial OPD d_1 can only be determined with a certain error e. With respect to the system in eq. (4), the OPD d_{1+m} for is

$$d_{1+m} = d_1 \prod_{i=0}^{m-1} \Omega_{1+i} + \sum_{i=0}^{m-1} \left[\Gamma_{1+i} \prod_{j=i+1}^{m-1} \Omega_{1+j} \right] \qquad (6)$$

with

$$\Omega_i = \frac{2k_i k_{i+1} - k_{i+1}}{2k_i k_{i+1} + k_i} \quad \text{and} \quad \Gamma_i = \frac{k_{i+1}\gamma_i + k_i \gamma_{i+1}}{2k_i k_{i+1} + k_i} . \qquad (7)$$

Then the error Δd_{1+m} at the index *1+m* with respect to d_1 is calculated with equation (5):

$$\Delta d_{1+m} = e \cdot \prod_{i=0}^{m-1} \Omega_{1+i} \qquad (8)$$

Figure 3 shows a simulation for varying error values in the initial condition between *100 µm* and *300 µm* (OPD) and the measurement error to the whole line profile after having subtracted a best-fit line which does not influence the course of the measured surface.

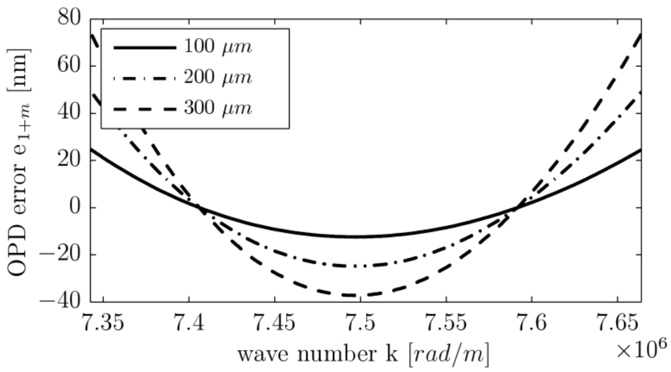

Fig. 3: Determination error e_{1+m} while solving the OPD profile with an initial error *e* for the OPD value d_1 and after the subtraction of a best-fit line.

This result shows, that the maximal error in the determination is lower than one per mill of the initial error value.

Experimental Results

In order to verify the given signal evaluation as well as the whole sensor principle, a measurement result of the resolution standard *RS-M* (*SiMETRICS GmbH)* [6] is presented in the following section. This consists of a set of gratings with a pitch value of *400 µm* in the measured area. The stated nominal height of the gratings is *90 nm*, hence the nominal OPD *d* is *180 nm*. Figure 4 shows the measurement result obtained by evaluating the phase with a complex wavelet transformation and using the model based algorithm.

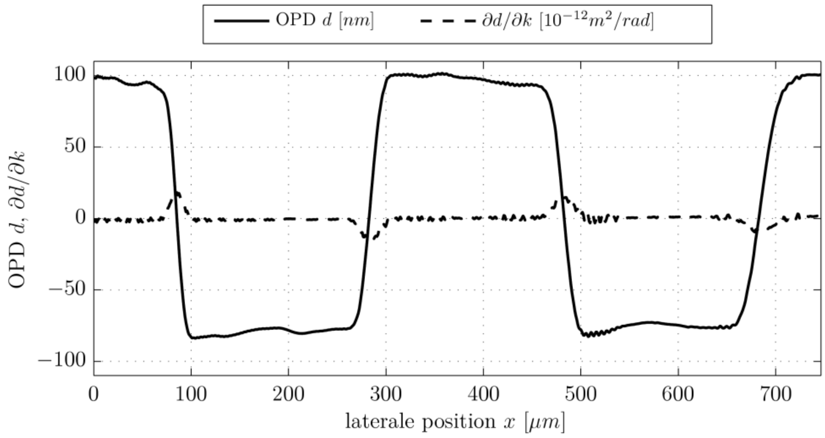

Fig. 4: Measurement result of the resolution standard RS-M with pitch *400 µm* and nominal OPD *180 nm*.

Since this specimen is axially symmetric with respect to the horizontal plane, it is assumed as an initial condition that the mean slope of the OPD *d* is equal to zero. By using an ordinary edge detection algorithm, a mean pitch of *200.29 µm* with a standard deviation of *3.5 µm* has been determined. Two different lines have been fitted into both the upper and lower parts of the OPD. The mean distance between both the lines indicates the mean OPD of the grating and is equal to *175.7 µm*, which differs from the nominal height by *2.5%*. However, the nominal height is only given approximately in the corresponding datasheet.

Conclusion

In this paper, a line sensor concept, that allows determining the height profile of a line on the object's surface without continuous mechanical scan, has been presented. Since both height information and lateral position are encoded in the same interference signal, a combined signal processing, which consists of a phase evaluation followed by a model-based approach, has been proposed. The given measurement showed good reconstruction results. However, the model-based approach is dependent on a priori information about the measured object which are necessary to generate an initial value for the reconstruction. Errors in this initial value will influence the determination of the whole height profile, but it has been shown that the expected error is very low with respect to changes in the initial value.

Acknowledgments

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