Γ-Profilometry on rough surfaces

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We present first results of Γ-profilometry on rough surfaces. Γ-profilometry is a new technique for interferometric shape measurement, based on spatio-temporal sampling of the coherence function. The main benefit is the combination of high precision with an inherent robustness against mechanical distortions.

1 Introduction

One of the main drawbacks of interferometry is the sensitivity towards mechanical vibrations [1]. Recently, we reported on a possible solution to this problem. It is based on spatio-temporal sampling of the coherence function of light reflected by an object [2]. The technique does not require a reference wave and can be realized by means of a shear interferometric common-path architecture, making it inherently insensitive towards mechanical disturbances. Since it is based on sampling of the coherence function Γ, we refer to the method as Γ-profilometry. In the following, we will show that Γ-profilometry can also be applied to rough surfaces. We will derive an analytical model which is valid under the assumptions that the surface has a roughness of $S_a < 2$ µm and the illumination has a bandwidth of $B < 20$ nm. Finally, we will show experimental results using a step like object with rough surface.

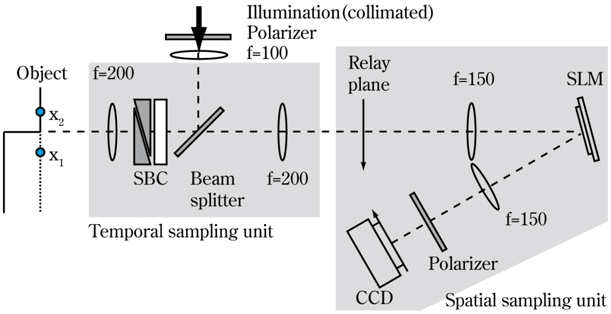

Fig. 1 *The setup used for Γ-profilometry consists of two units in $4f$-configuration. The common path functionality is based on birefringence. The Soleil-Babinet compensator (SBC) in the temporal sampling unit is a variable wave plate, which can delay light polarized along its slow axis with respect to light polarized along the fast axis. The illumination is linearly polarized between the birefringent axes. The spatial light modulator (SLM) in the spatial sampling unit creates a sheared twin image by diffracting light polarized along its slow axis into the diffraction order of a blazed grating, while light along the fast axis is reflected by the silicon back panel. Using the SLM, light from positions $\vec{x}_1$ and $\vec{x}_2$ in the object plane can be superposed in the image plane, while using the SBC, it can be mutually delayed by τ. The polarizer in front of the camera is again set between the birefringent axes to let the light interfere.*

2 From shape to coherence

The basic concept of Γ-profilometry can be seen from Fig.1, where the setup is explained in detail in the figure caption. The recorded intensity

$$I_R(\vec{x}) = I(\vec{x}_1) + I(\vec{x}_2) + \mathcal{R}\left\{\Gamma(\vec{x}_1, \vec{x}_2; \tau)\right\}, \tag{1}$$

depends on the real part of the coherence function Γ. Because of the object profile the light requires additional time to reach position $\vec{x}_1$ in the (dashed) object plane when compared to $\vec{x}_2$. The time delay τ_h can be attributed to the step height $\Delta h = c\tau_h/2$ using the speed of light c. The idea is now to use low coherent light to detect the shift τ_h by sampling $\Gamma(\vec{x}_1, \vec{x}_2, \tau)$ along the temporal axis τ. From a large number of finite differences Δh, we can reconstruct the objects shape through numerical integration.

Let us discuss the situation by means of scalar wave theory in order to assess the effect of a rough surface. In [2], we show that we can describe the coherence function in the camera domain as

$$\Gamma(\vec{x}_1, \vec{x}_2; \tau) = \sum_n u_n(\vec{x}_1) u_n(\vec{x}_2) \exp\left[-\mathrm{i}\omega_n(\tau - \tau_h)\right], \tag{2}$$

where the index n denotes spectral components and the u_n are the complex amplitudes corresponding to light with frequency ω_n. If the surface is optically rough, light reflected from it will produce speckles across the image plane and the u_n will follow a statistical distribution. As George et al have shown [3], for a small surface roughness $S_a < 2$ µm, speckle fields are mostly correlated (wavelength independent) for a considerable bandwidth of approx. $B < 20$ nm. This is an important requirement for multi-λ methods. We will make use of this and rewrite $u_n(\vec{x}) = a_n \cdot \bar{u}(\vec{x})$, where a_n is the spectral power of the illumination at frequency ω_n and $\bar{u}(\vec{x})$ denotes

DGaO Proceedings 2021 – http://www.dgao-proceedings.de – ISSN: 1614-8436 – urn:nbn:de:0287-2021-B020-0
submitted: 29.10.2021 – published: 17.11.2021

the statistical amplitude of the speckle field. Since $\bar{u}(\vec{x})$ is wavelength independent, we can write it in front of the summation

$$\Gamma = \bar{u}(\vec{x}_1)\bar{u}(\vec{x}_2) \sum_n S_{xx} \exp\left[-\mathrm{i}n\Delta\omega(\tau - \tau_h)\right] \Delta\omega, \quad (3)$$

introducing the power spectral density (PSD)

$$S_{xx}(n \cdot \Delta\omega) = \frac{|a_n|^2}{\Delta\omega}. \quad (4)$$

In Eq.3 we inserted $\omega_n = n \cdot \Delta\omega$ with $\Delta\omega = \omega_{n+1} - \omega_n$ being the spectral distance between neighboring frequencies. We can use the PSD to generalize this ansatz to a continuous spectrum by reducing the spectral distance to infinitesimal small distances $\Delta\omega \rightarrow d\omega$, which creates the continuous variable $\omega = n \cdot d\omega$ and we yield

$$\Gamma = \bar{u}(\vec{x}_1)\bar{u}(\vec{x}_2) \int_{-\infty}^{\infty} S_{xx}(\omega) \exp\left[-\mathrm{i}\omega(\tau - \tau_h)\right] d\omega. \quad (5)$$

Eq.5 represents a shifted and scaled version of the Wiener-Khinchin theorem. Hence, we expect to measure the Fourier transform of the PSD of the light source, but shifted by τ_h and scaled by the mutual speckle intensity $\bar{u}(\vec{x}_1)\bar{u}(\vec{x}_2)$.

3 Experimental results

As a proof of concept, we have measured the profile of a concentric step object with surface roughness of $S_a = 0.17$ µm. The steps are separated by a height of $\Delta h = 1$ µm and have a size of $\Delta r = 0.5$ mm. We have investigated the object with 6 shears (spatial sampling) and for each shear we have recorded 460 intensities for different values of τ (temporal sampling), where $\Delta\tau = 0.38$ fs. We used a light emitting diode as light source with a central wavelength of $\lambda = 625$ nm and a spectral bandwidth of approx. $B = 17$ nm. In Fig.2, we see the background intensity $I_0(\vec{x};\vec{s}) = I(\vec{x}) + I(\vec{x} + \vec{s})$ corresponding to a horizontal shear of $|\vec{s}| = 0.25$ mm. The diagram to the right hand side shows the real part of the coherence function for a dark (red) and a bright (blue) location in I_0. We can clearly see the scaling indicated by Eq.5, when we assume that dark areas of I_0 correspond to low coefficients $\bar{u}(\vec{x}_1)\bar{u}(\vec{x}_2)$.

From all 6 finite difference distributions we have numerically integrated the object shape, which can be seen from Fig.3. The surface shape has been accurately determined. The variations across the flat parts of the object are $\sigma = 230$ nm which does reasonably agree with the roughness of $S_a = 0.17$ µm. From earlier measurements on specular flat surfaces, we know that the statistical measurement uncertainty of the system is approx. $\sigma_m = \pm 35$ nm [2].

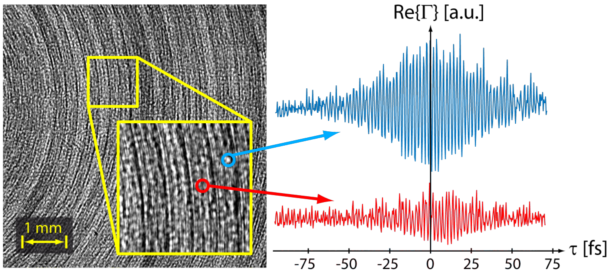

Fig. 2 *The temporal dependence of the coherence function at two different positions of the background intensity $I_0(\vec{x};\vec{s}) = I(\vec{x}) + I(\vec{x} + \vec{s})$, with the horizontal shear adjusted to $|\vec{s}| = 0.25$ mm.*

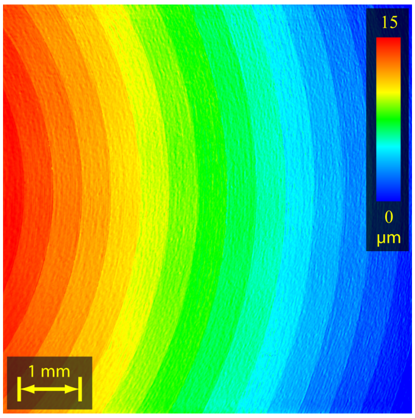

Fig. 3 *Resulting profile of a diamond turned concentric step object with roughness of $s_A = 170$ nm: The 1 µm steps are clearly visible. The surface variations are determined to 230 nm.*

4 Conclusions and Outlook

We have shown that Γ-profilometry can be applied to rough surfaces. Yet, we had to make rather restrictive assumptions to arrive at the presented analytical model. In future work, we will therefore address the limitations of the method with respect to the surface roughness and the bandwidth of the illumination.

Acknowledgement: We acknowledge support from the Deutsche Forschungsgemeinschaft (DFG) for the project Γ-Profilometry (contract no. 265388903).

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