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Form and Mid-Spatial-Frequency Measurement of Unknown Freeform Surfaces

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Summary:

Components with freeform surface give optical designers more degrees of freedom and can reduce the size and weight of optical systems significantly. However, one cannot manufacture it, if one cannot measure it. Thus, measurement systems have to evolve simultaneously. To meet up with these highly demanded requirements, we have developed a new measurement technique for freeform specular surfaces. This measurement technique is able to detect form and mid-spatial-frequency characteristics for known and even unknown freeform surfaces.

Keywords: metrology, surface characterization, freeform surfaces, experimental ray tracing, specular surfaces

Introduction

With optical components having spherical or aspherical surfaces, designers are limited in the design of optical systems, as occurring aberrations have to be compensated by other optical components. Using components with freeform surfaces can help prevent aberrations to occur or compensate easier. This reduces the number of optical components needed and gives designers the opportunity to create lighter and more compact designs, e.g. folded telescopes with freeform mirrors [1].

However, with the development of a new type of optical components comes the need for measurement systems to verify the manufacturing. This need has not been fulfilled sufficiently yet. We target this need with a measurement technique called Experimental Ray Tracing (ERT) [2]. It has initially been introduced in 1988 and has proven its abilities in several applications like characterization of optical systems and secondary optics for LEDs or refractive index measurement [3-5]. In this paper we present how to use ERT for the reconstruction of known or even unknown freeform surfaces.

Methodology

The original setup has been proposed to measure optical components in transmission. Obviously, this does not work for specular surfaces. Thus, we have altered the setup in a way that an incident ray with the direction $\boldsymbol{i}$ is pointed onto the surface under test (SUT) under a certain angle. At the point of intersection $\boldsymbol{I}$ with the surface, the ray is reflected into a new direction $\boldsymbol{r}$. A schematic sketch of the setup is shown in Fig. 1. This direction is dependent on the direction of the incident ray and the surface normal $\boldsymbol{g}$. By determining the positions $\boldsymbol{C}_1$ and $\boldsymbol{C}_2$ of the redirected ray in two parallel planes, the direction

$$\boldsymbol{r} = \boldsymbol{C}_2 - \boldsymbol{C}_1 \tag{1}$$

of the reflected ray can be detected.

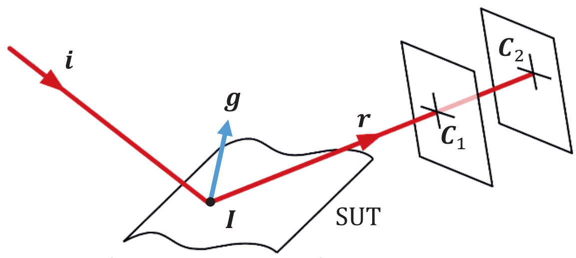

Fig. 1. Schematic sketch of the setup with the incident ray direction $\boldsymbol{i}$, the point of reflection $\boldsymbol{I}$, the normal $\boldsymbol{g}$, the reflected ray direction $\boldsymbol{r}$ and the two detected ray positions $\boldsymbol{C}_1$ and $\boldsymbol{C}_2$.

Having the incident ray direction $\boldsymbol{i}$ and the reflected ray direction $\boldsymbol{r}$ and their corresponding unit vectors $\hat{\boldsymbol{i}}$ and $\hat{\boldsymbol{r}}$, the unit vector

$$\hat{\boldsymbol{g}} = \frac{\hat{\boldsymbol{r}} - \hat{\boldsymbol{i}}}{\sqrt{2 \cdot \left(1 - (\hat{\boldsymbol{i}} \cdot \hat{\boldsymbol{r}})\right)}} \tag{2}$$

of the normal can be determined using vector geometry [6]. So far, this shows how one single point is observed. To get information about multiple points on the surface, the SUT is moved in lateral directions. This leads to a field of surface normal vecotrs. Introducing a coordinate system, the field of normal vectors can be converted into surface slopes. Using appropriate numerical integration methods, the surface can be reconstructed from the slopes [7].

Measurement setup

To perform experiments according to the methodology described above, proper hardware solutions have to be found. The incident ray is represented by a narrow laser beam with a diameter of $100\ \mu\mathrm{m}$. A linear xy-linear table performs the lateral displacement of the SUT. The movement directions of these stages also provide the direction of the coordinate system for the surface reconstruction. The detection of the reflected beams direction is realized by using a camera with a blank chip on a linear stage. Moving the camera realizes the parallel detection planes. Using centroid calculation methods on the detected intensity distribution leads to the beam position. A photo of the setup is shown in Figure 2.

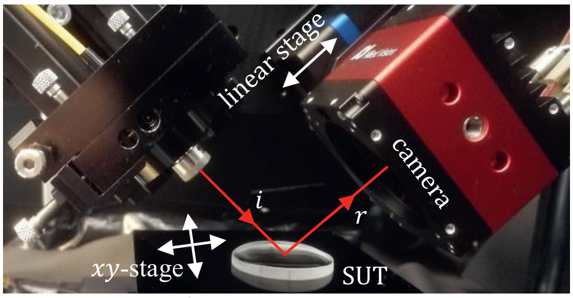

Fig. 2. Photo of the experimental setup with the incident ray direction $\boldsymbol{i}$, the reflected ray direction $\boldsymbol{r}$ and the hardware components.

As SUT we have chosen a polynomial freeform. The surface follows the function

$$s(x,y) = 3.5 \cdot 10^{-3} \cdot x^2 - 2.5 \cdot 10^{-3} \cdot y^2 - 2.5 \cdot 10^{-5} \cdot x^4 + 3.5 \cdot 10^{-5} \cdot y^4. \quad (3)$$

The surface has a circular clear aperture of $24\ \mathrm{mm}$ within it shows a PV sag of appr. $500\ \mu\mathrm{m}$ and a max. surface angle of appr. $10°$. The SUT has been sampled with an even grid with $100\ \mu\mathrm{m}$ sample distance over the clear aperture. This leads to a total number of 45217 sample points. The sample is shown as the SUT in Figure 2.

Results

The results show that the measurement technique was able to reconstructed the surface as one can see regarding the reconstructed surface sag shown in Figure 3. Subtracting the model from the reconstructed surface und subtracting the first 36 Zernike terms from the deviations, one can see the mid-spatial-frequency deviations detected by the measurement. Regarding these mid-spatial-frequency deviations, shown in Figure 4, one can see fabrication marks as well as three fiducials added for better orientation of measurement results.

Conclusion

In this paper, we have proposed a new measurement technique for the measurement of known and unknown freeform surfaces. The results show that the technique is able to reconstruct the SUT while detecting mid-spatial-frequency deviations simultaneously.

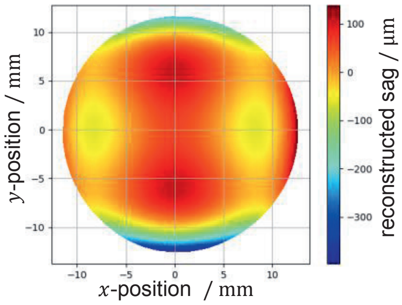

Fig. 3. Diagram of the reconstructed surface.

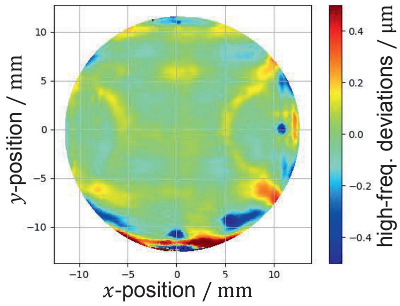

Fig. 4. Diagram of the mid-spatial-frequency deviations of the reconstructed surface from the model.

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