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Investigation of dynamic influences in tilted-wave interferometry

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Abstract. Aspherical and freeform lenses allow for compact optical systems and have therefore gained high interest in optics. The interferometric measurement of these forms is a challenge, for which the tilted-wave interferometer (TWI) has been developed. To evaluate the measurement uncertainty of the TWI, both the static and the dynamic influence parameters have to be investigated. In this work, we focus on the dynamic influences on the measurement data of the interferometer. To this end, the individual influences as well as their point of insertion into the process chain are identified. Then the measurement of the interferogram data is modelled as a Monte Carlo simulation. The propagation of different influences through the data process chain to the optical path length differences (OPDs) is also simulated, and the resulting variation of the OPDs is estimated. Furthermore, the variation of the OPDs resulting from measured interferogram data is investigated for comparison. The analysis and quantification of variation of the OPDs along with its contributing influence sources are important steps on the way towards a full uncertainty estimation of optical form measurement with the TWI.

1 Introduction

Aspherical and freeform surfaces have gained high interest in optics due to their ability to form compact lens systems that can correct image aberrations with few optical elements. To enable their highly accurate production, accurate measurement systems capable of measuring these surfaces are in high demand. However, large deviations from flat or spherical shapes lead to high fringe densities in classical interferometry, making these surfaces challenging to measure. Therefore, the tilted-wave interferometer (TWI, [1]) offers a promising solution by utilizing a 2D microlens array and solving an inverse problem to reconstruct the surface form under test from the measured interferograms. To achieve high surface reconstruction accuracy, both the optical model of the TWI and the optical path length differences (OPDs) between the test arm and the reference arm of the interferometer, which are determined from the measured interferograms, have to be known accurately. The OPDs are especially affected by dynamic disturbances such as unstable illumination, imprecise phase measurement, image detector noise, etc. To investigate the measurement uncertainty of a TWI, the knowledge of the magnitude and effect of these parameters is of high importance.

In this investigation, we have used a digital twin of the TWI [2] together with a Monte Carlo approach to identify individual sources of uncertainty. We have also analysed them in terms of their impact on the variation of the OPDs. To this end, we have analysed the propagation of the sources of uncertainty through the data process chain of the TWI. Moreover, we have related the results to estimates of the variation of the OPDs gained by conducting experiments. The investigations presented here are based on the software and hardware realization of the TWI at the Physikalisch-Technische Bundesanstalt (PTB) [3].

2 Method

2.1. Investigation of individual parameters

The distribution and magnitude of individual uncertainty influence parameters of the OPDs can be investigated either by experiment, as, for example, in the case of the image sensor noise that is analysed from many consecutive measurements, or by prior knowledge. In addition to the magnitude, the way in which the OPDs are affected is also of importance. For example, different parameters can either directly influence the physical OPDs within the interferometer, the phase measurement, or the image acquisition of the interferograms.

2.2 Monte Carlo simulation

To analyse the influence of the different parameters on the OPDs calculated from the measured interferogram data, a Monte Carlo simulation of the measurement process and data process chain is performed. Undisturbed OPDs of a virtual specimen are therefore simulated by raytracing using a digital twin of the TWI. Subsequently, variations directly affecting the physical OPDs, such as wavelength instabilities, can be added. After this, the OPDs are converted to phase information, which is then converted

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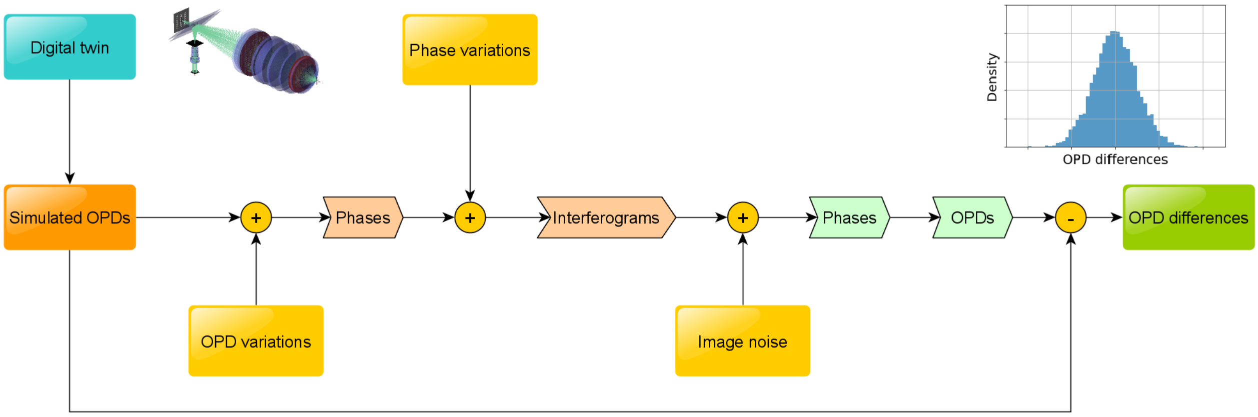

Fig. 1. Diagram of the Monte Carlo simulation process. The simulated OPDs are modified by the addition of OPD, phase, and image variations, and the OPD difference is calculated.

to a set of five different phase-shifted interferograms, which are used for the phase determination (see [4]). At the interface of this conversion, errors affecting the phase measurement, such as imprecise phase-shifting elements, are introduced. The resulting interferograms are converted to image data, and disturbances affecting the image data, for instance, image sensor noise or image clipping are added. The artificially generated interferograms are then processed in the same way as the measured interferograms in the TWI measurement process are usually processed: The five phase-shifted interferograms are used to retrieve the phase using Hariharan's phase retrieval [4] and Goldstein's phase unwrapping algorithm [5] to determine the OPDs. The difference of the disturbed OPDs and the original simulation can then be analysed by statistical methods. The process is depicted in Fig. 1. With this framework, the effects of different uncertainty parameters can either be analysed individually or in combination.

2.3 Experimental measurement

The experimental estimation of the variation of the OPDs can be performed by consecutive measurements of the same test specimen at the same measurement position within the TWI. With an appropriate number of measurements and precautions to keep the experimental setup stable for the required time, the mean of the OPDs and their variations can be determined. With this method, only the total variations can be determined, without knowledge of the error sources contributing to the variations. Nevertheless, the experimental result is important to compare the results to the virtual experiments and check the assumptions made.

3 Discussion

Quantifying the variation of the OPDs is crucial to the estimation of the measurement uncertainty of the TWI. Therefore, Monte Carlo methods are used to investigate the influence of individual uncertainty sources on the resulting OPDs. This not only helps to predict the variation of the OPDs from the uncertainty sources, but also helps future optimizations of the system. Furthermore, the investigation of the variation of the OPDs calculated from consecutive experimentally measured interferogram data helps to evaluate the quality of the simulation. The comparison between both approaches can moreover be used to evaluate the fraction an individual source contributes to the overall OPD variation.

The estimated OPD variation can be used for further analysis of the form measurement uncertainty of the TWI by applying the respective error influences to simulation experiments with the digital twin of the TWI. In combination with other uncertainty sources and appropriate data analysis methods, this can lead to an uncertainty budget of the TWI and therefore help to establish the TWI as a highly accurate measurement system for aspherical and freeform surfaces.

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