Position Tolerancing of Freeform Phase Plates for Variable Extended Depth of Field Imaging

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Abstract: We discuss and analyze the sensitivity to misalignment errors of a freeform phase plate pair designed to enable variable extended depth of field imaging. Methods and impacts of the errors on system performance are demonstrated.

1. Introduction

Imaging systems with high Numerical Apertures (NA) have short Depths of Field (DoF) that cause problems in applications such as microscopy at high magnification by producing images with in-focus and out-of-focus regions. Therefore, methods to increase DoF have been of special interest. Freeform optics are starting to play major roles in imaging systems [1]. As an example, it has been shown that implementing freeform phase plates at the exit pupil of the imaging system increases DoF [2-4]. Generally, for each imaging system, a specific phase plate is designed which can introduce an increased number of parts and cost. As a result, phase plates that enable Extended Depth of Field (EDoF) for multiple imaging systems are desirable.

Previously, researchers have shown that the addition of a phase plate with a cubic surface profile enables EDoF [2]. Based on this, we first designed three Cubic Phase Plates (CPP) for three lenses with different NA values. These CPPs were then replaced by one pair of transmissive freeform phase plates, with Quartic surface profiles given by:

$$Z_f(x, y) = \beta\left(\frac{x^4}{4} + xy^3\right), \tag{1}$$

where the β coefficient depends on the maximum relative shift between the phase plates, the refractive index of the phase plates, and the amplitudes of the cubic phase plates that are being replaced. This Quartic Phase Plate Pair (QPP) enables EDoF for multiple lenses using relative shifts along the x-axis between the pairs [5]. This concept is very similar to the design of variable focal length lens introduced by Alvarez in 1967 [6].

While increasing DoF using phase plates strongly depends on the design path and criteria, it is also important to consider misalignment errors and their effects on optical performance. In this paper, we quantify the sensitivity of EDoF phase plates to misalignment errors based on the effects of rotation and displacement on drops in the system's Modulation Transfer Function (MTF) at selected frequencies. The phase plates' misalignment errors were studied with respect to the imaging lens. To reduce system sensitivity to misalignments and loosen the tolerances, it was assumed that the detector can move along the z-axis, and the lens and phase plate pair are mounted on a tip/tilt stage to enable rotations about the x- and y-axes. The misalignment errors included rotation about and decenter along all Cartesian axes for the phase plates (Fig. 1).

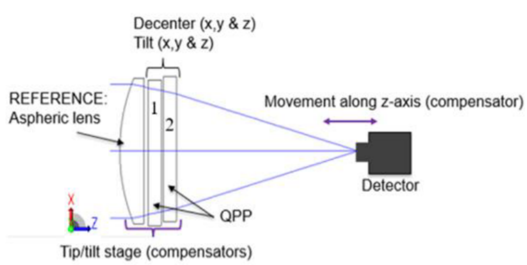

Fig. 1. Misalignment errors and compensators.

2. Methods and Example

The phase plates were assumed to be made from Polymethyl Methacrylate (PMMA) and operate at 633 nm wavelength. We replaced three CPPs (designed for 0.25, 0.33, and 0.5 NA lenses) with one QPP to achieve similar through-focus spots and extend DoF with fewer components. Figure 2 shows the through-focus spot diagram and MTF plot (at best focus) for the QPP EDoF system with the 0.25 NA lens as an example. To enable EDoF for this specific lens NA, the quartic phase plates were each shifted 0.270 mm in opposite directions along the x-axis.

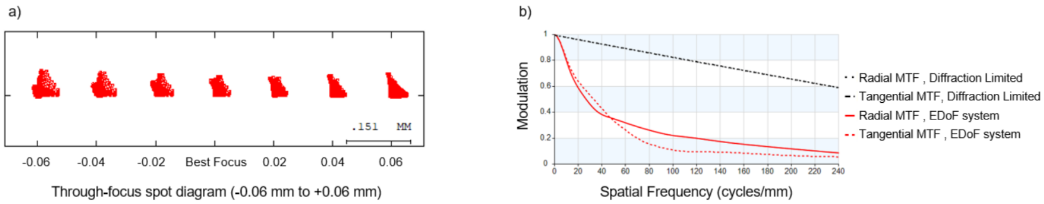

Fig. 2. a) Through-focus spot diagram and b) MTF at best focus for the 0.25 NA lens with QPP.

The tolerancing criteria were set to allow an MTF drop of 0.1 from the nominal value at specific frequencies for each system. Two tools were used to perform the tolerancing within CODE V. First, the wavefront differential tolerancing method (TOR) was used to calculate the changes applied to the wavefront due to the presence of misalignments [7]. Second, the Interactive Tolerancing tool was used to fine-tune the tolerance limits based on performance loss. As an example, we show in Table 1 the tolerance analysis for the QPP EDoF system with a 0.25 NA lens. The calculated values for the compensators were 0.34 mm for the detector movement along the z-axis, and 1.32 and 1.60 degrees for the lens and QPP x- and y-rotations.

Table 1. Tolerance results for EDoF system with 0.25 NA lens and QPP.

Misalignment type	1st element	2nd element
x-decenter (mm)	0.05	0.05
y-decenter (mm)	0.05	0.05
x-rotation (degrees)	1.15	1.15
y-rotation (degrees)	1.15	1.15
z-rotation (degrees)	0.03	0.03
Lens and element 1 air gap (mm)	0.20	
Element 1 and 2 air gap (mm)	0.20	

3. Discussion

We performed tolerance analyses for EDoF systems with CPPs and QPP for lenses with three different NA's. Initial results show that the EDoF systems with CPPs are less sensitive to misalignment errors compared to the QPP EDoF systems, especially for lower NA values. Also, it is evident that among different rotational misalignments errors for the EDoF system with QPP, the performance is most sensitive to rotations of the phase plates around the z-axis (clocking) due to the rotational asymmetry of the phase plates. Additionally, the initial comparison for systems with different NA values shows that as the relative shift (along the x-axis) between the phase plate pair increases for higher NA lenses, the system becomes less sensitive to x- and y-decenters. Based on discussions with the mechanical engineering team, we have confirmed that the tolerances are achievable and work is underway to build the EDoF systems and experimentally characterize their performance.

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5. References

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