Mitigation of optical aberrations using binary-amplitude masks and digital image processing

Gonzalo Muyo, Tom Vettenburg, Andrew R. Harvey
School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, UK
a.r.harvey@hw.ac.uk

Abstract: We report the design of binary-amplitude masks that in conjunction with digital restoration enable mitigation of optical aberrations. Essentially, the design process aims to reduce destructive interferences in the optical transfer function.

OCIS codes: (070.0070) Fourier optics and signal processing; (100.0100) Image processing; (110.0110) Imaging systems; (110.1758) Computational imaging; (110.2990) Image formation theory; (110.4850) Optical transfer functions.

1. Introduction

Binary-amplitude masks located at the aperture stop can be optimized to mitigate optical aberrations and allow sufficient information to be recorded for the recovery of a sharp image using digital image restoration. In comparison to phase-based correction techniques that employ reflective or transmissive wavefront modulators, this technique offers lower complexity and cost, and can be accomplished efficiently from ultra-violet to far-infrared wavelengths with a wide variety of fixed or agile spatial-light amplitude-modulation techniques.

In the next section, we briefly described two approaches for deriving coded masks to mitigate a given optical aberration. In the first approach, significant image contrast across all spatial frequencies is obtained by employing a low-dimensional mask optimization that selectively block destructively interfering parts of the aperture [1], such binary-amplitude masks are here referred to as *contour masks* and can be considered to be the amplitude mask equivalent of the phase mask proposed by Love *et al* [2, 3]. An analytical expression for the upper limit of the modulation transfer function (MTF) of an imaging system with large aberrations and a contour mask is also reported. In the second approach, the masks are numerically optimized by exhaustive search over a high-dimensional discretised space of binary values as proposed by Stayman *et al.* [4]. In section 3, we show examples of the performance of coded masks in the presence of common aberrations with monochromatic light. Finally, the performance of a set of agile coded masks is evaluated for imaging through the aberrated conformal surface of a missile dome.

2. Derivation of binary-amplitude contour masks

The contour mask $M(u)$ for an aberration characterized by an optical path length variation $l(u)$, blocks areas of the pupil along the iso-phase contour lines and is given by as:

$$M(u) = 1, \forall u \,|\, \left(l(u) - \varphi_0 - t \cdot u + \frac{\Delta\varphi}{2} \right) \bmod 2\pi \le \Delta\varphi,$$

where u is the normalized pupil coordinate, $\Delta\varphi$ is the maximum permitted phase-difference between any two points in the pupil. The parameters φ_0 and t are the reference phase and the tip-tilt respectively and can be optimized. The introduction of tip-tilt, t, merely displaces the imaged field-of-view. As demonstrated by Vettenburg and Harvey in [1], the optical transfer function of a given contour mask contains no nulls and, in the limit for large aberrations, can be written as

$$OTF_m(\nu) \approx \frac{2\pi}{\Delta\varphi} \frac{MTF_{dl}(\nu)}{\pi^2} \sin^2\left(\frac{\Delta\varphi}{2}\right) \le \frac{2}{\pi^2} MTF_{dl}(\nu),$$

Where MTF_{dl} denotes the diffraction-limited MTF. Note that the magnitude of the mask MTF is maximized when is $\Delta\varphi = \pi$ and transmission of 50%. This mask will yield approximately 20% of the contrast of the diffraction-limited MTF. More importantly, the expected MTF is independent of the magnitude of the aberrations: it is limited only by the contrast and spatial resolution of the amplitude modulator.

An alternative mask optimization approach, significantly more computationally demanding, consists in a rigorous search over a high-dimensional discretised mask space in which the magnitude of the MTF is maximized across the spatial frequency domain [4]. This approach allows optimizing a set of discrete binary-amplitude mask whose MTFs are complementary: one mask MTF may contain nulls at some frequencies as long as those frequencies are present in another mask MTF. Such imaging system requires a reconfigurable shutter array to acquire a sequence of coded images that are subsequently processed via a multi-frame restoration algorithm to produce a sharp image. By using several binary-amplitude masks in combination with image restoration, one is able to recover spatial frequencies that are lost as a result of the aberrations present in an imperfect imaging system.

3. Results

The contour masks displayed in the left column of Fig.1 are optimized for two representative aberrations: astigmatism and coma. Black areas represent opaque areas of the mask, and the hue of the transmissive areas indicates pupil phase. The plots in the central column Fig.1 show the MTFs for the non-masked, aberrated pupils: the low values and nulls in the MTFs are readily apparent. The MTFs in the right column correspond to the masked, aberrated pupils and show a significant increase in the MTFs. Even considering that the total transmitted intensity is reduced by the mask to approximately 50%, the MTF for the masked pupil is significantly increased for all spatial frequencies and there are no nulls, thus enabling a high quality image to be recovered by digital processing.

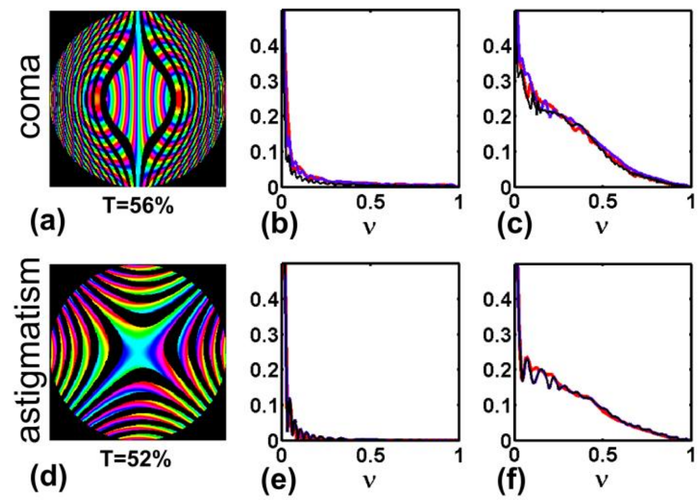

Figure 1. Aberration compensation of coma (a-c) and astigmatism (d-e) and with a root-mean-square optical-path difference of 2λ . The aberration phases and contour masks with the relative transmission noted below are shown in (a,d,g). The tangential (black), sagittal (blue), and diagonal (red) MTF without mask in (b,e,h), and with mask in (c,f,i).

We consider now a sequence of two 16×16 binary-amplitude masks optimized to correct aberrations introduced by the ellipsoidal dome of a missile, see Fig. 2, with monochromatic light. The imaging system employs a reconfigurable shutter array at the aperture stop which can change the binary-amplitude pattern depending on the field of view of interest, as in foveal imaging. The magnitude of the aberrations introduced by the dome increases gradually with field of view (FoV) up to a maximum of 4 waves at ±45 degrees. After optimization using a differential evolution algorithm, two masks for various FoV are obtained, see Fig.2 for (0^{o}, 45^{o}), the transmission of both masks is approximately 60%.

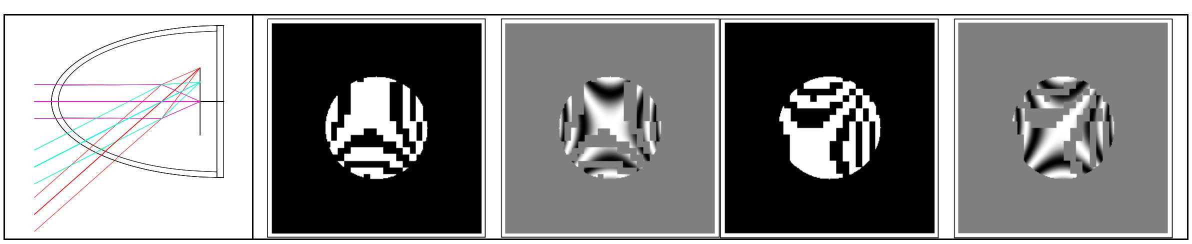

Figure 2. (left) 2D layout of the missile dome optical design from Zemax (Right) Two coded masks optimized to improve performance at FoV (0^{o}, 45^{o})..

The tangential and sagittal MTFs of the system at (0^{o}, 45^{o}) with and without masks are shown in Fig.3. Clearly, in spite of the 40% loss of transmission of the amplitude masks the magnitude of coded MTFs is significantly higher than the conventional MTF and, more importantly, the coded masks have eradicated the nulls across most of the spatial frequency space by reducing destructive interferences in the optical transfer function.

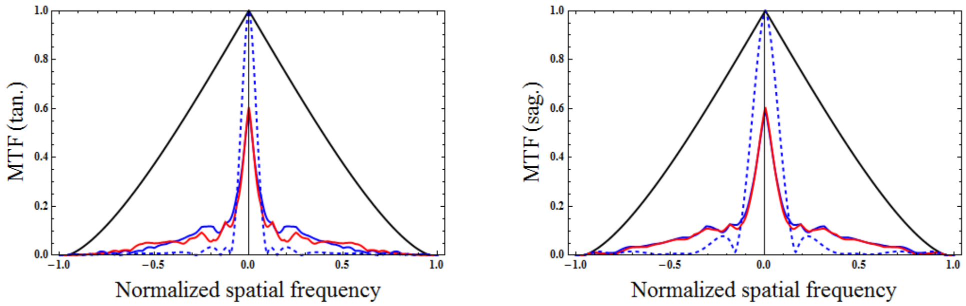

Figure 3. Tangential (left) and sagittal (right) unrestored MTFs of the diffraction limited (solid black), aberrated (dashed), mask 1 (solid blue) and mask 2 (solid red) systems. MTFs scaled according to transmission. FoV at (0^{o},45^{o}).

The restored images using regularized multi-frame recovery are displayed in Fig. 4 for both conventional and binary-amplitude mask systems. Both systems use a sequence of two masks (fully open in the conventional system) and the images are acquired with the same integration time, so they have equal additive Gaussian noise levels but different SNR at the time of detection (peak SNRs of the conventional and amplitude-mask images are 37dB and 30dB respectively). At left we see the conventional image; at right one can see the improved performance using the optimized masks..

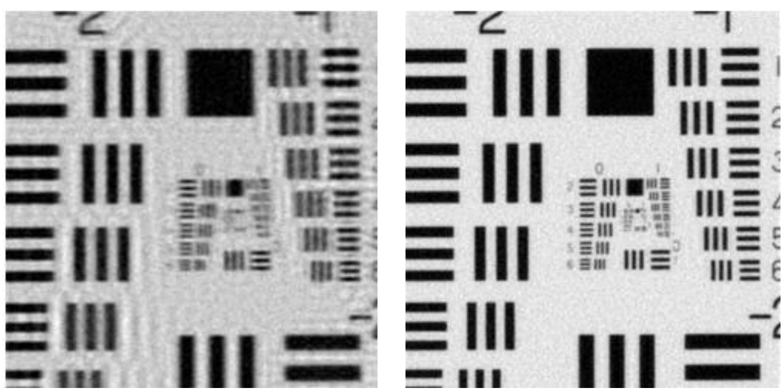

Figure 4. Restored images from the conventional system (left) and the amplitude-mask system (right) for FoV at (0^{o},45^{o}).

4. Conclusions

We have shown that binary-amplitude masks can be designed to correct for phase aberrations to yield, in general, an improved MTF (approximately 20% of the magnitude of the diffraction-limited MTF for contour masks). The absence of nulls and the relatively modest reduction in the MTF allows for digital recovery of a high quality image. Although the benefits of the masks are most pronounced for monochromatic imaging, it might be reasonable to think that two or more masks could give better results for multiple wavelengths.

References

[1] T. Vettenburg and A. R. Harvey, "Correction of optical phase aberrations using binary-amplitude modulation," J. Opt. Soc. Am. A **28**, 429-433 (2011).

[2] G. D. Love, N. Andrews, P. Birch, D. Buscher, P. Doel, C. Dunlop, J. Major, R. Myers, A. Purvis, R. Sharples, A. Vick, A. Zadrozny, S. R. Restaino, and A. Glindemann, "Binary adaptive optics: atmospheric wave-front correction with a half-wave phase shifter," Appl. Opt. **34**, 6058–6066 (1995).

[3] P. M. Birch, J. Gourlay, G. D. Love, and A. Purvis, "Real-time optical aberration correction with a ferroelectric liquid-crystal spatial light modulator," Appl. Opt. **37**, 2164–2169 (1998).

[4] J. Webster Stayman, N. Subotic, and W. Buller, "An analysis of coded aperture acquisition and reconstruction using multi-frame code sequences for relaxed optical design constraints," Proc. SPIE **7468**, 74680D (2009).