

Non-Directional Modulation Transfer Function for Optical Surfaces with Anisotropic Mid-Spatial Frequency Errors

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Abstract:

Sub-aperture manufacturing creates anisotropic surface errors, and modulation transfer functions (MTF) not well represented by 1D cross-sections. We present a 1D ‘non-directional’ MTF for specification and characterization of optical surface errors. © 2019 The Author(s)

OCIS codes: (110.4100) Modulation transfer function; (220.0220) Optical design and fabrication.

1. Introduction

The most notable works for studying the impact of mid-spatial frequency (MSF) errors on optical performance assume these errors are statistically distributed or very well structured. Early studies on the impact of sub-aperture fabrication tool errors date back to evaluation of surface quality of diamond turned optics by Church and Zavada in 1975 [1]. However, their statistical approach requires that perturbations are small, and errors are random with no structured spatial frequencies in the Power Spectral Density (PSD) [2]. Marioge and Slansky considered the impacts of structured rotationally periodic waviness on image quality in 1983 [3]. More recently, Tamkin [4,5] has published on impacts of structured MSF errors on the Modulation Transfer Function (MTF).

Despite great progress, these works use the conventional 1D MTF representation, which plots a horizontal or vertical cross section of the MTF. This method can provide incorrect or misleading performance information if the MTF is anisotropic. Many MSF errors resulting from sub-aperture fabrication methods are not symmetric over the beam footprint, leading to asymmetric and non-uniform MTF. Calculation of a 2D MTF is straightforward but can be more difficult to interpret. In this paper, we present an approach that captures key information from the 2D MTF and presents it in a more familiar 1D format. This ‘non-directional’ MTF can be used for characterization and specification of both symmetric and anisotropic optical surface errors.

2. Method and Discussion

Several experimental examples of measured surface textures that result in asymmetric MTFs are presented in Fig. (1). Even an unrealistic and perfectly symmetric surface texture could yield to an asymmetric MTF for off-axis field angles. This also holds true when the surface is not positioned at the pupil and as a result the beam footprint does not cover the entire surface.

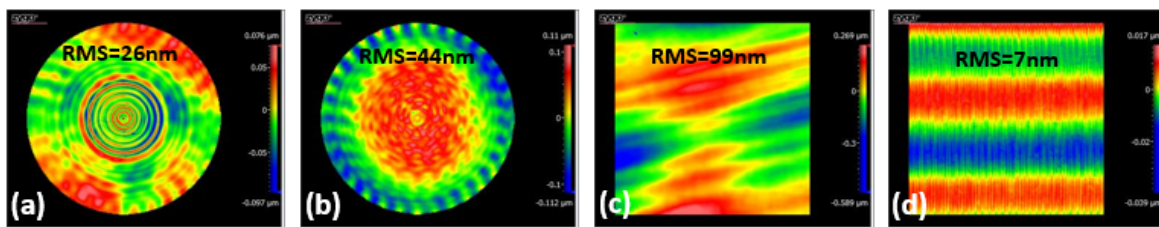


Fig. 1. Measured mid-spatial frequency surface errors. Experimental MSF errors have structured textures but are not necessarily symmetric.

Here, we present a method to calculate a non-directional 1D MTF and a measure of MTF uniformity. It is common for designers to specify contrast (MTF) at several spatial frequencies. For example, an MTF specification is often given as a “not-to-be-less-than” contrast at Nyquist, half-Nyquist and quarter Nyquist frequency across several field points, sometimes out to the full field diameter [5]. Therefore, we need to have the minimum MTF values for all frequencies and in all directions to confidently rely on a 1D representation of MTF. To do this, we first calculate the 2D MTF, and then rotationally extract the minimum value for each spatial frequency f (where $f = \sqrt{f_x^2 + f_y^2}$).

We refer to the resulting plot of minimum modulation transfer value at each spatial frequency as the ‘non-directional MTF.’ We also calculate the standard deviation of changes in MTF for each spatial frequency to get a measure of uniformity, which can help to identify which spatial frequencies are more problematic.

3. Examples

To demonstrate this idea, we consider a MSF texture of the form shown in Fig. 1(a) on the surface of a calcium fluoride ($n = 1.5576$) $f/10$ lens in the ultraviolet region ($\lambda = 157\text{nm}$). Fig. (2) illustrates MTF simulations and non-directional MTF analysis for this system. In Fig. 2(b), the non-directional MTF indicates that the optical performance is actually worse than predicted by a standard 1D MTF cross section. The MTF uniformity plot in Fig. 2(c) shows that the MTF non-uniformity is a maximum at about one-half of the lens’s cutoff frequency.

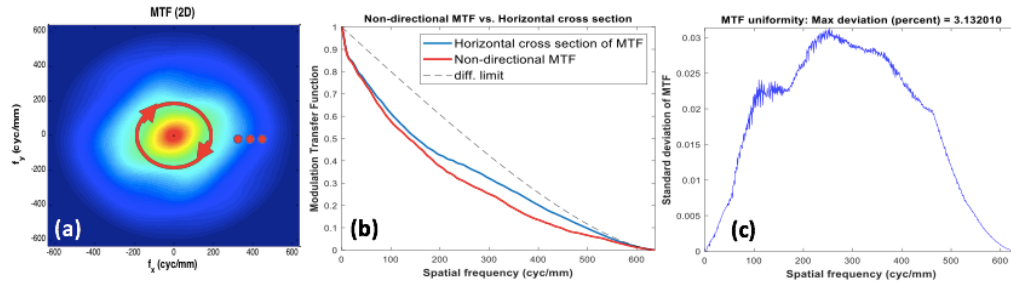


Fig. 2. (a) Simulated on-axis 2D MTF for a lens with MSF texture presented in Fig. 1(a). (b) Comparing Non-directional MTF (red) with horizontal cross section of MTF (teal). (c) MTF uniformity plot with maximum deviation of 3.13% at 253 cycles/mm.

We next validate our methodology using synthetic MSF surface data from a diamond-milled surface. Figure 3(a) assumes a diamond milled surface fabricated with a tool-tip radius of 1mm and 40 μm step-over. To have a more realistic surface, a sinusoidal thermal error of 1 cycle/mm with peak to valley of 150nm is added to the cusp errors. We know by experience that these grating-like sinusoidal and cusp textures diffract the incident beam in the direction of these periodicities, which directly translates into the system MTF (Fig. 3(b)). A 4 mm $f/25$ PMMA ($n=1.4934$) lens at the pupil operating at $\lambda = 0.532\mu\text{m}$ is assumed for these optical performance simulations. Figure 3(c) shows an excellent match between the non-directional MTF and lowest minimums of the horizontal MTF cross section.

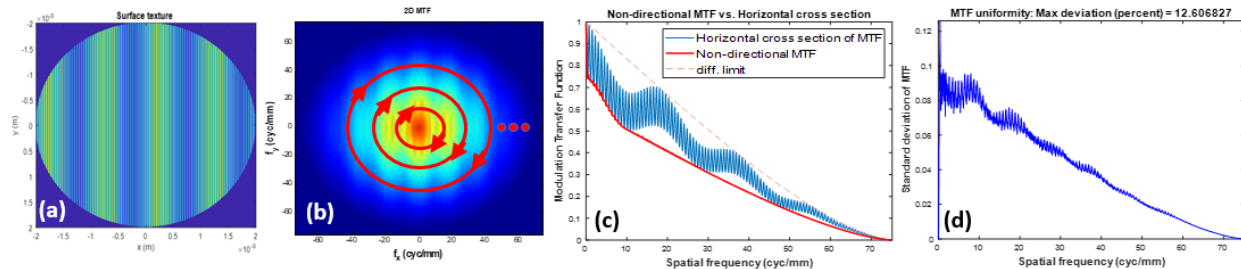


Fig. 3. (a) Example diamond milled MSF error. (b) on-axis 2D MTF. (c) Non-directional MTF (red) and horizontal cross section of the MTF (teal). (d) MTF uniformity plot with maximum deviation of 12.6% at 0.4 cycles/mm.

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5. References

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