Characterizing the resolving power of laser Fizeau interferometers

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ABSTRACT

Optical fabrication relies on precision metrology over a wide range of lateral scales. Consequently, an important performance parameter for Fizeau interferometers is the instrument transfer function (ITF), which specifies the system response as a function of surface spatial frequency. Advances in test procedures, instruments and automated analysis techniques now enable reliable ITF characterization independent of many traditional sources of error. Results here show the ITF for a commercial 100-mm aperture interferometer with spatial frequency response ranging from 0 to 1500 cycles per aperture.

Keywords: Interferometry, Fizeau, optical metrology, lateral resolution, optical transfer function, instrument transfer function, mid-spatial frequency.

1. INTRODUCTION

The imaging performance of optical components depends in part on the spatial frequency content of its surfaces [1]. The surface spatial frequency content is often divided into qualitatively-defined regimes. The low frequency regime consists of spatial frequencies that define the general surface form, often described by functions like Zernike polynomials, while the high frequency regime characterizes surface roughness or finish and is usually described with statistical parameters such as $S_a$ or $S_q$. The region in between is termed the Mid-Spatial Frequencies (MSFs) and are responsible for small angle light scattering which if not controlled can reduce image quality and contrast. MSFs can expose process defects related to part manufacture, such as ridges or deformations from diamond turning processes or small tool polishing machines. The dominant MSFs are often produced from one or more critical dimensions in the fabrication process. For example, in the case of diamond turning it could be the tool feed rate relative to the part rotation rate while for small tool polishing it would be the size of the polishing pad. Figure 1 shows typical surface tool marks from a diamond turning process and the corresponding surface power spectral density along the vertical direction.

![Surface tool marks and power spectral density](image)

Figure 1: Surface tool marks from a diamond turning process and the surface power spectral density (PSD) along the vertical direction [1].
2. THE LASER FIZEAU INTERFEROMETER

The laser Fizeau interferometer (Figure 2) is an established high-precision instrument for measuring optical components and systems [2]. Laser light is directed to the cavity produced by a movable reference surface and the surface under test while a camera records a series of interferograms representing cavity interference with the reference surface moving to produce well-defined interference phase shifts. Analyzing the interference intensity as a function of phase shift for each camera pixel determines the surface topography relative to the reference surface. Alternatively, phase estimation from a single camera frame using polarization or spatial heterodyning with carrier fringes enables high-speed measurements for difficult environments [3, 4].

Figure 2: A typical laser Fizeau interferometer configured for phase shifting interferometry showing major components

When fabricating high precision optical components, one of the performance characteristics of optical metrology instruments is the ability to detect and accurately measure mid- and high-spatial frequency surface deviations from the ideal figure. The demand to extend the instrument measurement range have driven camera formats to higher and higher density. Current systems now provide surface height measurement noise of <1nm for 1-sec data acquisitions over 11.6 million pixels, providing surface information encompassing both low and mid-spatial frequency regimes [5]. Optical designers have been challenged to keep up with this trend so that the optical resolution of the complete system is consistent with this dense sampling [6]. The accuracy of a surface topography measurement is influenced by many factors, including the optical performance of the measuring instrument itself, the cavity environment and the characteristics of the measured surface. For surfaces that do not depart too much from the reference surface shape, the first two factors dominate the residual surface error.

3. THE ITF

The instrument transfer function or ITF characterizes the lateral resolving power of optical instruments for 3D surface topography measurements. The ITF is a more complete and meaningful description of instrument response than a single lateral resolution number such as the Raleigh limit or the camera pixel size [7]. The ITF catalogs the response of the system to pure surface sine wave patterns as a function of frequency. As such, it is particularly useful for anticipating and sometimes correcting for variations in the reported PSD of an object surface related to the metrology [8, 9].

The ITF for a profile relates to an input surface height $h(x)$ as a function of a lateral object-space coordinate $x$. The corresponding surface spatial frequency content $H(f)$ is calculated from a Fourier Transform $F$. The measured topography similarly has a spatial frequency content $H'(f)$, but the reported surface heights $h'(x)$ in object-space coordinates are weighted by the ITF $(f)$, as follows:
where $F^{-1}$ denotes the inverse Fourier Transform [10]. ITF graphs are plotted with the horizontal axis representing surface spatial frequencies, with each frequency corresponding to a single component sinusoid in the surface structure.

The ITF is in principle a linear, shift-invariant filtering process that describes the instrument, independent of the object. Intuitively, we might expect the modulus of the ITF to follow the modulus of the optical transfer function OTF often used for analyzing the imaging properties of optical systems. The OTF is the Fourier Transform of the point spread function, and is a linear filter for complex amplitude in a fully coherent optical system [10, 11]. However, depending on the type of instrument, there may be stricter limits of validity for the ITF for a phase-measuring interferometer than for the more general OTF. It can be demonstrated that the ITF is indeed linear and closely follows the OTF provided the range of angles for the light diffracted from the object surface topography is fully captured within the pupil function of the instrument [7, 12]. This in turn implies practical limits on the surface height variations for linear ITF response that fall into two regimes: (A) Large spatial periods, corresponding to overall form, and (B) sub-wavelength variations in surface heights at spatial periods approaching the lateral resolution limits of the instrument. An additional limit on validity is that the ITF is shift invariant only over local areas of the field of view, given that no optical instrument is perfectly isoplanatic.

4. **EMPIRICAL MEASUREMENTS OF THE ITF**

A straightforward approach to calibrating the ITF is by measuring a surface with known spatial frequency content and evaluating the ratio

$$\text{ITF}(f) = \frac{H'(f)}{H(f)}$$

(4)

The design and fabrication of test specimens for measuring ITF rely on the fidelity of raised features on the scale of a few nm. An approach used before is to fabricate an artifact with a variety of periodic patterns that are linearly chirped in frequency and oriented in different directions [13]. This type of test specimen is conceptually straightforward, but fabrication is difficult and the final product is not easily verified for quality across the full frequency range.

Our approach has been to use the 3D equivalent of the edge spread function test [14], relying on sharp step features across the full aperture of a 100mm diameter super-polished disk shown in Figure 3. The specimen has two edges, one horizontal and the other vertical, and includes additional features lying in the quadrants defined by the two main edges to aid in properly focusing the instrument. These features are fabricated using conventional lithography methods, assuring geometrically precise, sharp, high quality features and the super-polished substrate minimizes high frequency noise.

The calculation of the ITF follows from comparing the frequency content of the measured step to an ideal, perfect step, the calculation of which are outlined in Figure 4. Perpendicular edge profiles across the step (called traces) are extracted from the measured surface over the field of interest. The traces are differentiated to produce a line spread function (LSF) and then Fourier transformed to produce a local ITF. The local ITFs are then averaged over the field of interest to produce the region ITF.

This approach is valid provided that the step height is much smaller than the illumination wavelength (30nm compared to the HeNe wavelength of 633nm in this case) assuring that the instrument stays in the linear phase regime so the measurement results are an accurate indication of the ITF. In order to use Eq. (4), the step edge must be much sharper than the instrument resolution so it is legitimate to assume a “perfect” step. High resolution interference microscopy showed that the step edge 10-90% transition width was everywhere less than 2 microns (Figure 5), much smaller than the sampling resolution of a common 100-mm laser Fizeau system.
Many factors can influence the fidelity of an ITF measurement. Environmental disturbances can degrade or accidentally exaggerate ITF results, motivating the use of methods that minimize vibration influences. For that reason, vibration-robust that preserve the ITF sensitivity over the full spatial frequency spectrum are preferred over conventional phase shifting [15]. Further, because the ITF is sensitive to focus, a successful strategy for removing operator error is to optimize the ITF measurement in post processing by digitally propagating to the plane of best focus [16].
Leveraging new camera formats and with redesigned optics to accommodate the higher sampling density, the next generation of laser interferometers can measure both low and mid-spatial frequency regimes of high performance optical systems and lenses [5]. Figure 6 shows an ITF measurement from one such system compared to the theoretically expected ITF after accounting for optical resolution, pupil position and camera MTF. The instrument has a 100mm aperture and a camera with a sampling density of >11.5M pixels (3400 × 3400 pixels), for a spatial sampling period of ~30microns. An aperture stop sets the measurement design limit at 15 cycles per mm with an ITF > 40% to prevent aliasing. Measurements at different field positions along the step height features in the test sample verify that the expected spatial frequency response is consistent over the full surface area.

![Figure 6: ITF measurement results for a system with design resolution limit of 15 cycles/mm or 1500 cycles/aperture, compared to theoretical expectations.](image)

5. SUMMARY

The need to minimize mid-spatial frequency errors in optical assemblies and lenses, coupled with advances in camera technology, instruments, test procedures and analysis techniques has supported new high performance laser interferometer designs with well-defined transfer function characteristics over broad spatial frequency ranges with reduced sensitivity to several traditional sources of uncertainty and operator error.

REFERENCES