Proceedings

ASPE 2017 Spring Topical Meeting

Precision Engineering and Optics: What are the Limits of Precision, and How to Characterize Them?

April 24-25, 2017

American Society for
Precision Engineering

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LIMITS TO RESOLUTION IN OPTICAL DIMENSIONAL METROLOGY

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DEFINING RESOLUTION

Resolution is one of the most frequently misunderstood and poorly defined descriptions of performance [1]. Misconceptions include the role of spatial and temporal bandwidth, the effects of filtering, and fundamental effects related to physical optics, detector noise, and aberrations.

A contributor to the confusion is lack of precision in the definition of the term “resolution”. In optical imaging, resolution refers to the ability to clearly distinguish between closely spaced points or features, often according to limits established by physical optics. In distance and surface height measuring systems, resolution is limited by digitization or measurement noise. To better understand the limits of resolution and how to characterize them, we need to consider these two concepts independently, and perhaps adjust our vocabulary accordingly.

RESOLUTION IN 2D AND 3D IMAGING

With densely-sampled images, we encounter limitations based on diffraction or optical quality that limit the ability of instrumentation to resolve closely-spaced image features [2]. Lateral resolution is the smallest center-to-center separation of features that still allows us to see clearly that there are two features present [3]. FIGURE 1 shows on the right two trenches formed by patterning silicon on a quartz substrate. The interference microscopy 3D image shows that there are indeed two lines present, although they appear blurred at this high magnification. As the center-to-center separation between the lines decreases, the optical resolving power of the instrument becomes a limiting factor in determining whether the two lines are clearly separated.

Modern laser Fizeau interferometers have cameras with over 5 million pixels, providing detailed lateral sampling of form, waviness and surface texture [4], The topography image in FIGURE 2 is for a diamond-turned disk with a surface height range of a few tens of nanometers. To take advantage of these large-format cameras, the optical system must be appropriate quality, with large limiting apertures.

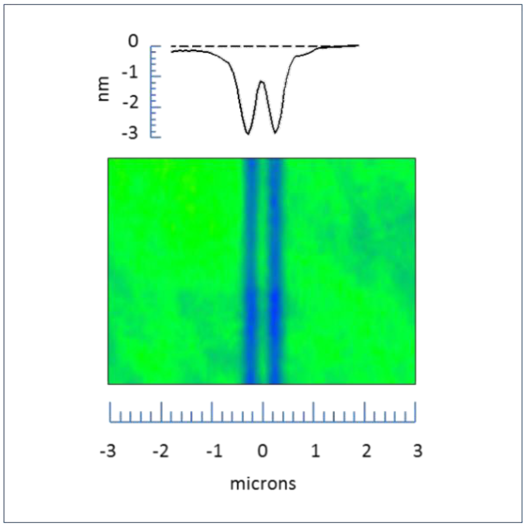

FIGURE 1: 3D interference microscope image of parallel trenches using a 100× objective with an NA of 0.85. The trenches are 200 nm wide and the center-to-center spacing is 440 nm

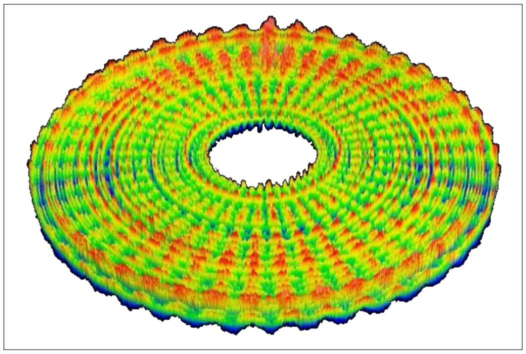

FIGURE 2: 3D image of a diamond-turned disk using a 100 mm aperture laser Fizeau interferometer.

It is common to quantify the lateral or imaging resolution of an instrument in terms of a single number, such as the Rayleigh limit [5]. Although more difficult to specify, the modulation transfer function (MTF) and its analog the instrument transfer function (ITF) in 3D metrology provide much greater information regarding instrument response as a function of line separation [6].

A simple linear ITF catalogs the response of the system to pure surface sine wave patterns as a function of frequency. In the limit of small amplitude (<< λ) or low frequency sine waves, we can predict the instrument response to the overall surface structure by mapping the Fourier components of the surface, weighted by the ITF, to the reported topography [5]. An attractive feature of the ITF characterization is that it corresponds closely to the power spectral density (PSD) evaluation of surface error in optical fabrication [7]. The foundations for a rigorous understanding of the MTF and the linear ITF are well documented in the literature [8]. More complete models allow for extending these ideas more generally to larger steps and slopes in coherence scanning 3D microscopy [9, 10].

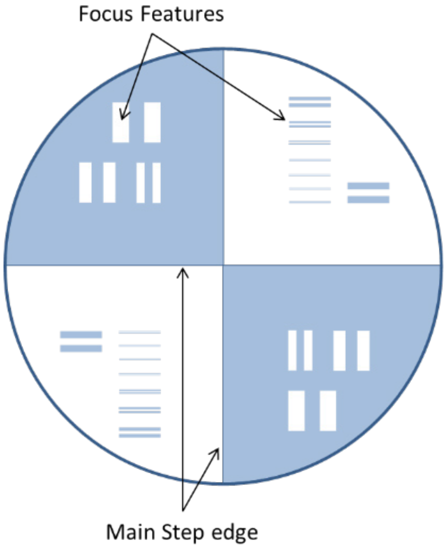

FIGURE 3: Patterned surface of an ITF measurement specimen with etched features for evaluating the edge spread function.

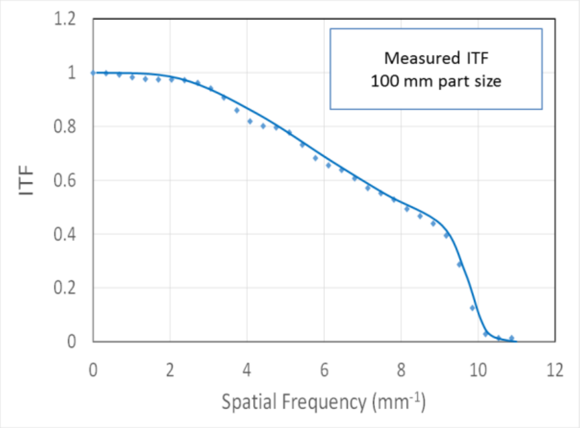

FIGURE 4: Example precision ITF measurement results showing a design resolution limit of 0.0625 mm or 1600 cycles/aperture.

For our measurements of ITF, we use the 3D equivalent of the edge spread function [11], relying on 25 nm sharp step features across the 100 mm full aperture of a super-polished disk. The test sample shown in FIGURE 3 has both a horizontal and a vertical edge, and additional targets to aid in properly focusing the instrument. The ITF calculation follows from comparing the frequency content of the measured step to an idealization of a perfect step.

FIGURE 4 shows an ITF measurement result, in this case for an instrument with a design maximum spatial frequency of 16 cycles/mm. Measurements at different field positions verify that the expected spatial frequency response is uniform over the full surface area. The steep slope at high frequencies is consistent with apertures in the optical system intended to prevent camera aliasing [12].

An important aspect of imaging resolution is that it relates to fundamental physical principles that have little to do with measurement noise. We can average the image in FIGURE 1 for days if we like, and perhaps gain an extra 10% in resolution simply from the improved quality of the image. But ultimately we are limited by the imaging principle, the wavelength, and the apertures within the optical system. Similar constraints apply to depth discrimination in confocal microscopy and optical coherence tomography. These limits do not apply, at least not in the same way, to our next topic.

RESOLUTION IN DISTANCE MEASUREMENTS

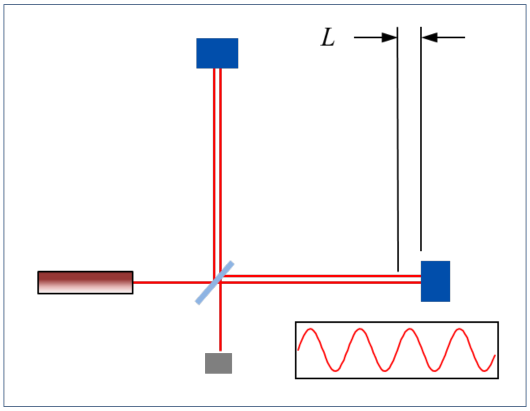

FIGURE 5: Interferometer for measuring the distance L .

Optical dimensional metrology typically involves one or more distance, displacement or surface height measurements with respect to a virtual reference point or plane in space. FIGURE 5 shows an interferometric sensor for measuring a distance or displacement L. The smallest detectable change δL is often called the "resolution". Of significance, δL is not related to the separation of two object points or distances at the same time, as in imaging resolution. As such, there is no absolute physical limit regarding how small δL can be. There is no Airy spot with which to contend as a fundamental limit.

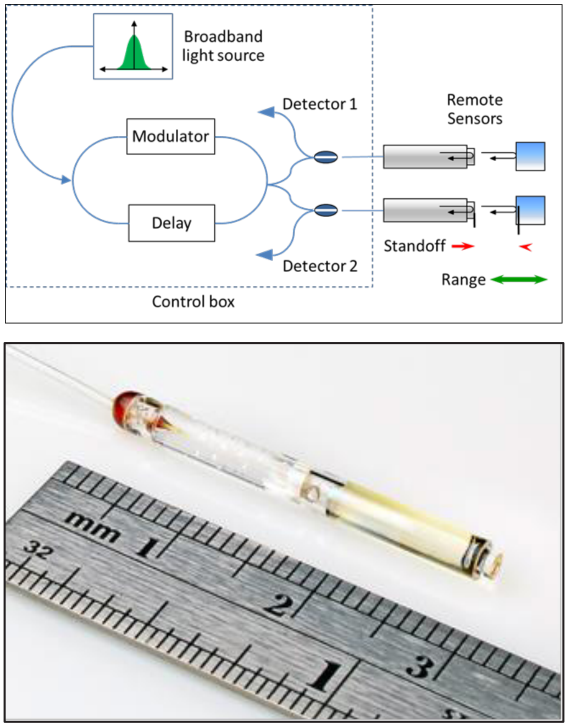

FIGURE 6: High-precision, fiber-based position sensing system [13, 14].

Assuming that we have a surplus of digitization for recording fine increments, the "resolution" of distance sensors is synonymous with random measurement noise. Consequently, proper specification necessarily includes the bandwidth or measurement time [1]. It also follows that with enough light source power, time and signal to noise, there is no lower limit to what is achievable in detector sensitivity. Modern precision sensors such as the fiber-based device shown in FIGURE 6 have 3σ noise figures in the 0.5 nm range at 10 kHz, compared to >250 nm limit for the lateral resolution in visual wavelength microscopy.

TABLE 1: Specifications for the precision sensing system shown in FIGURE 6.

Fiber sensor specifications [15]			
Digital Resolution	0.01 nm	Noise (3σ)	0.005 nm/√Hz
Data Rate	Max 208 kHz	Stability	1 nm / day
Channels	Up to 64	Non-linearity	± 1 nm

RESOLUTION IN SURFACE TOPOGRAPHY

Areal surface topography presents an interesting and sometimes confounding mixture of the two resolution concepts discussed here. The measurement in 3D measuring microscopy provided by interferometers, confocal and focus variation instruments is an array of height measurements over an imaged surface area. The ability to separate features on the topography map is related to imaging resolution, whereas the change in surface height that we can detect is governed by measurement noise. It is unfortunate that there is widespread use of the term "vertical resolution" for such instruments, as it promotes confusion of the two concepts. This is evident in specification sheets for these instruments, which, with few exceptions, make no mention of measurement speed or time bandwidth when quoting vertical resolution [16]. Draft ISO standards for calibration will perhaps mandate a correction to this practice [17].

Apart from model-based methods comparable to scatterometry and enhancements to image clarity and correction for undersampling, 3D interference microscopes remain diffraction limited. Surface height "resolution", on the other hand, has room to advance based on quantum well depth, camera pixel count and data acquisition speed. The current state of the art for interference microscopy, for example, provides better than $0.1\text{nm}/\sqrt{\text{Hz}}$ over one million simultaneous height measurements [18]. Following the familiar $\sqrt{N}$ rule means that a 10 pm repeatability is achievable in 100 s. It is reasonable to consider methods and enabling technologies that can reduce this even further without breaking any fundamental limits.

THE LIMITS OF RESOLUTION

Here I have argued that characterizing the limits of resolution requires an adjustment in our vocabulary. It would be preferable in specification sheets and technical reports to reserve "resolution" for those metrology attributes that are constrained by our ability to clearly separate neighboring features or surface depths, as in 2D and 3D imaging. For distance measurements, including height measurements for widely-separated surface features, it would be better to quantify the measurement noise or the equivalent, taking care to note if it is a single standard deviation or a multiple thereof.

Once we are speaking a common language, there is a wide range of useful characterization techniques. For imaging resolution, sample specimens with closely-spaced features complement linear ITF methods based on the edge spread function and other techniques. For distance measurements, the corresponding noise levels can usually be determined from repeatability tests over a range of bandwidths. These characterization methods allow for sensible comparison of instrumentation, advances in performance, and adaption of measurement techniques to demanding applications.

ACKNOWLEDGEMENTS

The authors recognize the contributions of ZYGO scientists and engineers to the results shown in this paper. We also thank Prof. Richard Leach for his review of the draft manuscript.

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