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Design for metrology for freeform optics manufacturing

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Abstract

Freeform optical surfaces offer significant design opportunities but pose new challenges in metrology and manufacturing. Evolution in optics manufacturing processes have changed the surface spatial frequencies that must be measured. Optical surface definition is expected to be with respect to fiducials and datums which must be realizable at all stages of manufacture; uncertainty in that realization becomes important in some cases. Concurrent engineering is required, but appropriate data has not been collated for use by optical designers. One approach to providing such data is described.

Keywords: freeform optics, metrology, concurrent engineering, design for metrology,

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1. Introduction

Freeform optical surfaces are a rapidly emerging design form, which allows new design freedom and opportunities to develop optical systems with better performance in a given volume or a significant volume reduction for a given optical function [1]. Starting in the 1980s, an evolution began from load controlled full aperture optics fabrication to increasing use of small tool processes using ultra-precision machines and displacement control (such as diamond turning and milling machines) or combinations of position and dwell time control (such as magnetorheological finishing and computer-controlled polishing). These processes enabled cost-effective fabrication of on- and off-axis aspheric optical surfaces. Further advances in these processes and in design enable use of optical surfaces with no axis of invariance on or off the part [2,3].

Manufacturing of state-of-the-art optics does not conform to the conceptual structures of mainstream production. Concurrent engineering, taught to mechanical engineers often in sophomore year in the USA (see for example [4]), is a foreign topic academically in most optics and physics faculties, although one that is practiced in some vertically integrated optics manufacturing organizations. A significant fraction of state-of-the-art optics are developed using sequential processes; “completed” optical designs are passed off to “opto-mechanical engineers” who may negotiate with the optical designers before turning – often -- to small, specialized fabricators. The transition from systems of spherical and plano optics, dominantly produced by classical polishing processes, to aspheric and freeform optics is a driving force for change.

From the perspective of manufacturing, arrays of aspheric micro-optics and off-axis aspherics share many of the characteristics of freeform fabrication. The latter, however, pose additional metrology challenges, the topic of this paper.

2. Datums, assembly, fiducials, tolerances and ISO 10110

Elements of optical systems comprising spherical and plano (flat) surfaces have an “optical axis: typically defined by the outside diameter of the part acting as a datum after “centering” (see for example [5]). Aspheric optics have an axis (on or off the part) defined by the prescription and typically realizable in measurement of the surface.

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The ISO standard on preparation of drawings (ie specification) of optical elements and systems has separate parts for aspheric surfaces [6] and general (including freeform) surfaces [7]. It should be noted that the standard applies to optical elements as well as assemblies and systems. Hence, the designer's intent (if any) regarding assembly is not necessarily captured in an element drawing.

Since a freeform does not have an "optical axis", a "reference axis" is defined [7] as a "theoretical axis given by the optical designer which does not depend on the symmetries of the surface and usually represents the center of the optical path for the main function". The standard continues "… the position and orientation of the reference axis is defined by measurable references at and/or on the general surface…". Hence, according to the standard, acceptance of an element's surface shape is limited in part by the uncertainty in the realization of the coordinate system using fiducials and other references and the tolerances in positioning the surface with respect to the reference axis. Positional compensators (adjustments) allow optimization of the system wavefront error for both element placement and fabrication errors. These adjustments enable relaxation of tolerances on the optical surface at the price of increased system complexity.

One key difference between on-axis aspheric systems and freeforms is the limited ability with freeforms to use rotation of the optical elements about their reference axes to minimize rotationally varying system wavefront error arising from manufacturing errors in individual element surfaces. A related limitation arises in some optical methods of measuring surfaces. For tight tolerance rotationally invariant surfaces, rotations are used to separate errors in the part from errors in the test set-up in an analogous manner to roundness testing. This is not possible for freeforms.

Clearly concurrent engineering – specifically concurrent optical design, design for manufacture, design for metrology, and design for assembly – is required for appropriate allocation of tolerances.

In the early 1990s some work was done to enable "snap together" aspheric optical systems, i.e. systems in which no adjustments are provided [8]. This approach was limited to IR systems, primarily by the tolerances associated with machining of locating features and the capabilities of the machine tools available. The absence of adjustments tightens the tolerances on surface form and location.

More recent advances in machine design, including 4- and 5-axis ultraprecision systems where coordinate axis turning and micromilling can be implemented in a single set-up, has resulted in revived interest in "snap together" systems (see [9,10] for example). Recent publications describe snap together freeform systems [11], multiple optical surfaces on a single substrate [12] and monolithic systems [13]. One attraction of two separate surfaces on a single substrate is that the relative position location accuracy is determined by the (small) error motions of the precision machine. However, thermal effects scale with the substrate size, not the element size.

Coordinate systems should be realizable both in manufacturing steps as well as metrology – a key task in design for metrology. Further, design for metrology should be part of concurrent engineering that allocates tolerances based on system requirements and manufacturing and metrology capabilities.

3. Metrology method capabilities

One vision of concurrent engineering in advanced optics development would provide summary data to optical designers on the manufacturing capabilities integrated with optical design tools. For example, "soft" constraints in the optimization code might flag elements with apertures larger than can be fabricated or measured using equipment available in-house or tolerances tighter than the maximum permissible error on an available coordinate measuring machine.

A less ambitious approach, being developed within the Center for Freeform Optics (CeFO), is to develop a data hierarchy in which the capabilities of different metrology tools appropriate for measurement of form, mid-spatial frequencies (waviness) and surface finish of freeform optical surfaces. In addition to optics designers, the same data may be useful to fabricators. Target data characteristics include:

- "Coherent": the same data representations (from standards where possible) are used for different types of instrument;
- "Stratified": layers of information, with active links. The highest level data shows measurement technologies and capabilities to help down selection of approaches relevant to the most general description of the part to be tested. The lowest level gives detailed discussion of individual commercially available instruments and instruments in development, which could be used to measure the part under test; and
- "Curated": The source of the data used, at every level, will be reported. The user of the information can weigh manufacturer reported performance against data from other sources. For some of the generic instruments, examples are installed at CeFO sites. Performance test data and experience on those instruments are reported and the source of the data cited. In some cases, newer models have been developed, and appropriate data from the manufacturer are given (and sources cited).

This tool specific information on the capabilities of different instruments is akin to the Quality Information Framework (QIF) [14] although not planned to be integrated into enterprise management systems. The current implementation uses a text document (.docx or .pdf) with navigation links, viewed as a precursor to implementation in HTML.

Currently, there are 3 levels of information. Level 1 shows broad instrument capabilities by category (scanning white light interferometers (SWLI), contact profilometers, Fizeau interferometers, and coordinate measuring machines.

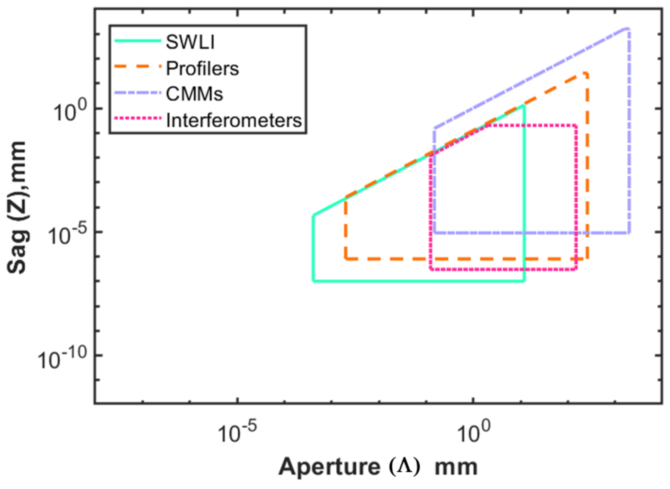

Figure 1: Generic instrument capability diagram

3.1 Generic instrument capabilities

Basic capabilities (and more detailed information at lower levels) are shown on a “Freeform Optics Metrology Capability Diagram” (FOMCD). This is based on the approach pioneered by Stedman [e.g. 15, 16] using amplitude-wavelength space (i.e. considering the optical surface prescription and topography in the Fourier domain). Notably, this representation is global; in some instruments better performance may be achieved over smaller apertures. Here we use “aperture” (projected maximum dimension of the optic under test) and “sag” (departure from the reference) which are more familiar to optical designers and optical fabricators and hence more appropriate for this use.

Note also that the FOMCD assumes smooth, continuous surfaces, especially for optical measurement methods. The FOMCD should be used with caution (if at all) when considering surfaces which give stronger diffraction effects [18].

Figure 1 shows a generic capability diagram; in the tool we are developing, there is an accompanying table with numeric values for the limits, the source of the information and/or how it was calculated. Note that the limits plotted appear as “hard limits”. In practice, these limits are more nuanced. For example, Z_{min} (the minimum sag or vertical resolution) in Figure 1 for a SWLI system is, in practice, noise limited. Trading-off resolvable amplitude with increased measurement time pushes down the minimum vertical resolution. At the same time,the minimum spatial wavelength “measurable” is a function of spatial wavelength. At the highest spatial frequencies, the instrument transfer function shows that the ratio of “true” to measured amplitude decreases as the spatial frequency approaches the Nyquist limit [17].

The original Stedman approach implies that instruments are limited at 1 cycle per aperture. This is clearly not true, for example when measuring optical surfaces with large base radii or designed astigmatism, which are measurable but noise limited.

In previous work [19], we attempted to capture these and other nuances, as well as retaining the original Stedman format. It is possible to plot a metrology capability diagram for a SWLI system, for example, showing multiple objectives (each discontinuity in the slope limit line represents a change of objective), the trade-off between measurement time and the noise floor, etc (Figure 2). Similarly, it is possible to show the effect of trace length and area measured in a sequential instrument such as a 3D profilometer. Industry feedback, however, suggested that the increased fidelity impeded understanding. Hence, we have focussed on the simplified diagram at the highest level of the information hierarchy, giving increased detail in subsequent levels, and using simple industry terminology.

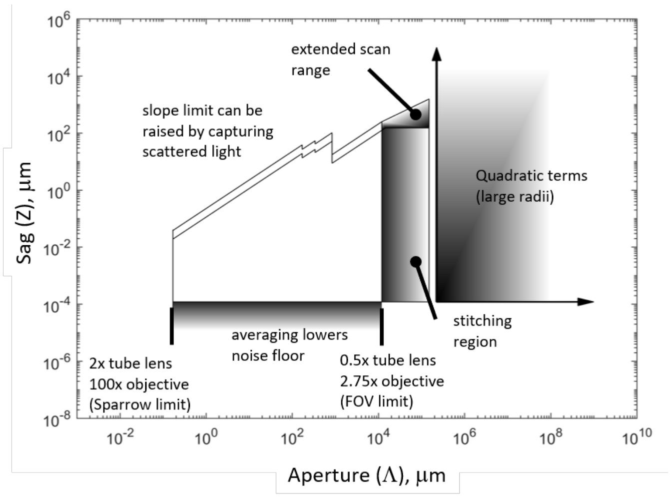

Figure 2: Adding information hinders comprehension

Figure 1 shows limits for a full aperture figure measuring interferometer. These limits are, in fact, specific to a particular measurement configuration. Fizeau interferometers are commercially available with a variety of “accessories” (transmission flats and transmission spheres) that allow for measurement of a range of departures from specified spherical base radii. Leaving aside the limitations imposed by “nulls”, commercial interferometers have limitations on radii that can be measured around the in-cavity focus[20] as well as limitation posed by the depth of focus in the field . We are working to develop an “angular capability diagram” which captures these limits in a manner analogous to the Stedman based capability diagram.

3.2 Generic technology details

Once the user of the tool has selected a “generic technology”, Level 2 provides a “Use case” and a “Discussion”. The use case is specific to measurement of optical surfaces. For a Scanning White Light Interferometer (also known by a number of other names including Coherence Scanning Interferometer), the stated use case is *“Area measurement of finish and mid-spatial frequencies (MSF) with stitching as required. Form metrology over limited aperture sizes (slope dependent) using stitching.”*. This use case deliberately ignores the many other applications of this type of instrument.

The discussion provides a brief description of the physical operating principle of the instrument (with references) and information on general characteristics and limitations of this type of instrument. At the end of the discussion are links to data on specific instruments; both commercially available instruments and instruments under development within CeFO are discussed.

3.3 Specific instrument data

The specific capability data are collected under the generic categories used in the higher levels. For example, the section on “Profilometers” currently contains details on five different instruments from 3 manufacturers. One is a custom instrument, based on a commercial profiler that is at a CeFO University site and two are at CeFO Affiliate member’s sites. Data on the remaining two are from their respective manufacturers.

In addition to “capability”, data resulting from experience with an instrument in a specific environment are included. Mostly, this data is based on work at the CeFO University sites. Examples are surface topography repeatability as a function of surface topography and surface damage (if any) introduced by contact profilometers.

4. Concluding remarks

Concurrent engineering is an important facet of cost effective, agile manufacturing and measurement of state-of - the-art freeform optics systems. This process will be eased if optical designers, fabricators and system integrators have, at their fingertips, data on manufacturability, including metrology.

In the context of “design for metrology”, the approach developed here allows optical designers, fabricators and metrologists to evaluate metrology capabilities in familiar language. At the earliest stages of the processes, they can check if metrology tools exist for the aperture (ie part lateral size) and sag (peak deviation of the optical prescription from the instrument’s reference surface). The data structure allows rapid navigation from selecting a generic method to detailed information on specific instruments and experience data on those tools.

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