Dynamic Metrology and Data Processing for Precision Freeform Optics Fabrication and Testing

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ABSTRACT

Dynamic metrology holds the key to overcoming several challenging limitations of conventional optical metrology, especially with regards to precision freeform optical elements. We present two dynamic metrology systems: 1) adaptive interferometric null testing; and 2) instantaneous phase shifting deflectometry, along with an overview of a gradient data processing and surface reconstruction technique. The adaptive null testing method, utilizing a deformable mirror, adopts a stochastic parallel gradient descent search algorithm in order to dynamically create a null testing condition for unknown freeform optics. The single-shot deflectometry system implemented on an iPhone uses a multiplexed display pattern to enable dynamic measurements of time-varying optical components or optics in vibration. Experimental data, measurement accuracy / precision, and data processing algorithms are discussed.

Keywords: Metrology, Optical Fabrication & Testing, Data Processing, Precision Optics, Freeform Optics, Deflectometry

1. INTRODUCTION

Precision optics are widely used in the aerospace, medical imaging, defense and consumer electronics fields, to name a few. An avenue of great interest for precision optics is freeform optics, which are rapidly gaining popularity because of the design flexibility they offer, in addition to allowing a system to have fewer elements and be lighter in weight. However, there are still some challenges that need to be overcome for manufacturing freeform precision optics. One such challenge is that during the manufacturing of these optics, the in-process (i.e., not-yet-completed) optical surface must be accurately measured to correctly guide the iterative fabrication process [1, 2]. One high precision solution is a customized null test (e.g., Computer Generated Hologram (CGH), null lens and / or deformable mirror [3]), but even then, its application is often limited to an expected null / near-null situation. Another challenge is that measurements must often be highly insensitive to noise, even in high vibration and other non-ideal environments. Several similar challenges result from the limited dynamic range offered by conventional metrology systems. For instance, in-process surface measurements could be made with orthodox interferometric null testing. However, the limiting factor is the inherent small dynamic range of nulling interferometry.

The presented metrology technologies allow for a much higher dynamic range than conventional measurement techniques. Here, we define dynamic range as the ratio between the largest and smallest values that the system can measure. Intuitively, one can think of a metrological system with a high dynamic range as having a high sensitivity over a large range of measureable configurations/environments. This allows us to realize why a system with a high dynamic range can be invaluable. With regards to precision optics testing (and the corresponding fabrication processes it guides), a large dynamic range can be extremely useful, or even necessary. We propose innovative solutions to address dynamic challenges in interferometry and deflectometry systems, both in the spatial and temporal domains. We also discuss a data

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processing methodology for obtaining the surface from measured gradient data that is particularly useful for high spatial resolution deflectometry systems.

Section 2 details the spatially dynamic metrology solution, which is an adaptive interferometric null testing system [4] and Section 3 discusses the temporally dynamic idea of instantaneous phase shifting deflectometry [5]. The proposed data processing technique can be found in Section 4 and Section 5 provides the concluding remarks.

2. DYNAMIC METROLOGY IN SPATIAL DOMAIN

The adaptive method presented here uses a deformable mirror (DM) as an adaptable null component for the optical surface under test. To determine the optimal shape for the DM, we use a stochastic parallel gradient descent (SPGD) algorithm [4, 6]. The final changes to the shape of the DM can be precisely measured by a deflectometry system (DS), which uses a display screen and a camera [4, 7, 8]. The on-demand null condition enables swift measurement of unknown freeform surfaces while keeping the entire system stationary (except the motion of DM actuators). When we incorporated this adaptive system into an interferometric null test, the resulting data showed outstanding results for the measurement of an unknown surface.

The system can be divided into the following three subsystems:

a) Interferometer

b) Deformable mirror (DM)

c) Deflectometry system (DS)

A schematic diagram of the overall system and its sub-systems can be seen in Fig. 1.

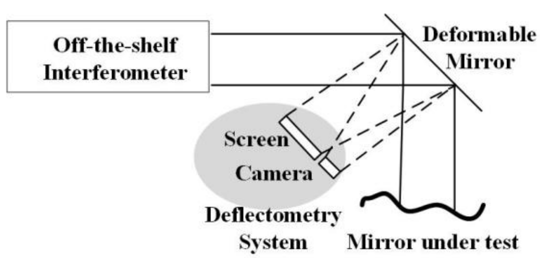

Fig. 1. Schematic of the proposed adaptive interferometric null system, with the three subsystems: Interferometer, deflectometry system and deformable mirror. [4]

Conventional DMs have a maximum stroke in the range of 10s of microns. In case a larger wavefront deformation is required for the adaptive interferometric null system, one workaround is to use a nominal static null component such as a CGH that can be used to offset the nominal deformation of the wavefront (e.g., deformation from the ideal optic under test). An important aspect to keep in consideration is that the DS of our set-up directly measures the surface of the DM, not the wavefront generated from it. Since effective optical testing and fabrication of freeform surfaces requires precise measurements of the mid-to-high spatial frequency error of the test optic, the proposed adaptive interferometric null testing system prerequisites a DM surface map of a significantly higher spatial resolution (such as 500 by 500 pixels) than most other general applications.

When an unknown test optic is first inserted into the metrology system, non-ideal (e.g., partial) interference fringes could be observed. Next, the DM is driven based on the results from the SPGD algorithm recovering near-null interference fringes. This creates an online null condition for the freeform surface. The interferometer measurements, along with the results from the DS are combined to produce the final surface shape data.

The SPGD based algorithm, that is used for fringe restoration will be heavily influenced by the merit function which is provided as the required target. A smart choice of this merit function will result in a quicker and more efficient convergence (to the ideal or threshold value). Fig. 2 shows a sample SPGD search case, showing the actual fringe restoration over time and a graphical representation. Zygo interferometer (4” Verifire ATZ) was used to measure the fringe. In this demonstration, the number of NaN (Not-a-Number) pixels in the measured fringe intensity map is chosen as the merit function.

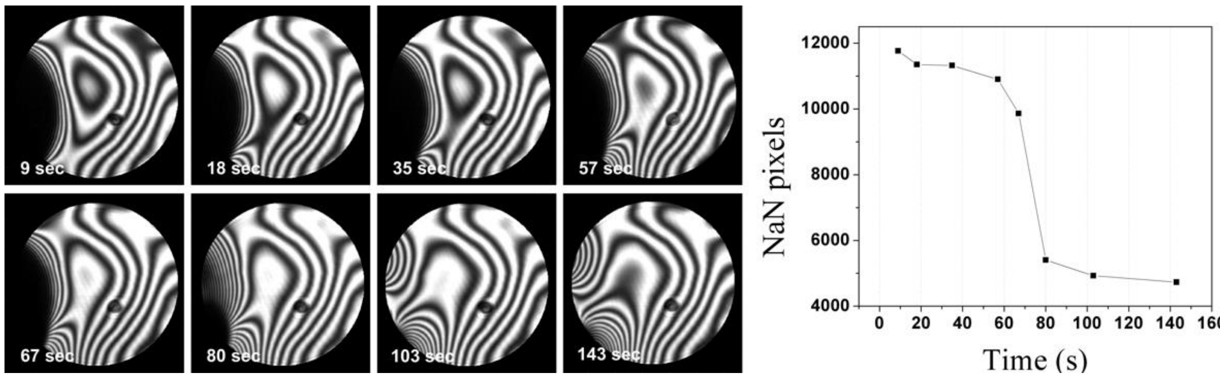

Fig. 2. Time evolution characteristics of a SPGD-guided fringe restoration process along with change in evaluation criteria that guides the process.

We set up another experimental system using a commercial interferometer (Zygo, Verifire ATZ) and a standard transmission flat [4]. The DM (Alpao, DM52-25) had 52 actuators and the DS consisted of an LCD (Mimo, UM710S, 7”, 800×480 pixels) and a camera (PointGrey, Flea3 1.3 MP Mono USB3 Visio, VITA 1300). The test object, which modeled an in-process optic, was a heavily distorted mirror that was prepared by random mechanical pinching that generated a large unknown surface shape error. A regular interferometric test could not produce a complete interference fringe over the entire object surface due to its limited dynamic range as shown in Fig. 3(a). When this system was measured with the proposed adaptive system, we obtained the full measurement shown in Fig. 3(b). The final surface shape had 15.79 μm PV (peak to valley) and 2.89 μm RMS (root mean square) values [4].

Measurements on this test surface cannot be verified since it is beyond the maximum measurement range of the standard interferometer. However, measurements on other mirrors (that were within the measurement range of the interferometer) prove that our adaptive method has good accuracy. As shown in Fig. 3(c)–(e), a mirror measured by both standard and adaptive system showed a small difference of 101.36 nm PV and 18.07 nm RMS, which translates to approximately 5.56% error in PV and 4.88% error in RMS (assuming the commercial interferometric measurement as reference) [4].

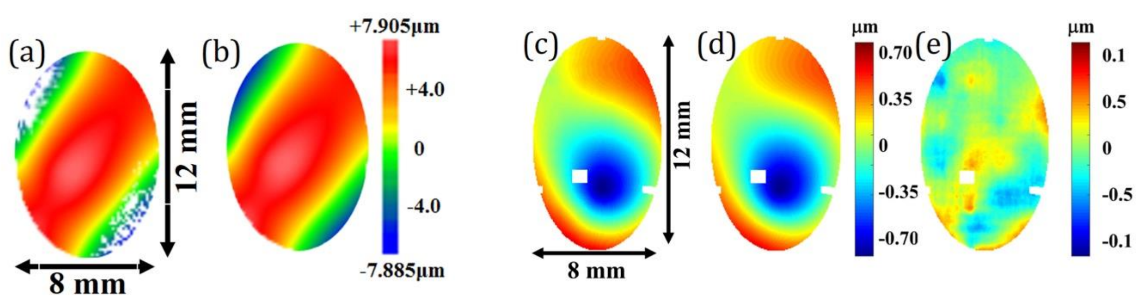

Fig. 3. (a) The initial interferometric measurement which does not cover the entire area due to standard interferometer’s limited dynamic range. (b) Final surface map based on data obtained by the proposed adaptive interferometric system. (c) Checking the validity; adaptive interferometric measurement (d) Checking the validity; standard interferometric method (e) Difference map of (c) and (d). [4]

The SPGD algorithm's convergence rate depends on several factors. The most important ones are image resolution, number of actuators of the DM, and computer specifications. Another performance limit of our method is set by the DM's actuator stroke range. An enhanced adaptive optics technology for the updatable null component would give more accurate results for a larger adaptable range. Other system limitations include uncertainties and imperfect ray-trace modeling of the entire system. However, as the test surface improves its shape during the fabrication process, the DM will eventually converge to a flat (or a modeled nominal shape), and those high-order errors and uncertainties would be greatly reduced.

3. DYNAMIC METROLOGY IN TIME DOMAIN

A temporally dynamic deflectometry system is presented here, that is based off of a generic deflectometry set-up, for measuring slopes, that has a display screen for generating known patterns and a camera to capture the resulting images. This can be thought of as a mapping between the camera and screen caused by the optic. Our method employs the use of a phase shifting based display pattern generation [9] to create the required mapping. Most other phase shifting methods change the display patterns over time and record several images to reconstruct the tested optical surface. These methodologies are limited in measurement of time varying events because they multiplex information in the time domain. In our instantaneous phase shifting deflectometry system, we multiplex all the necessary information into a single screen image and capture it with a single snapshot [5], thereby preserving the fidelity of time-varying information (within the constraints of an 'instantaneous' measurement). We have been able to use an iPhone as the camera and screen, proving that the system can be very compact and simple. A schematic of the system is shown in Fig.4.

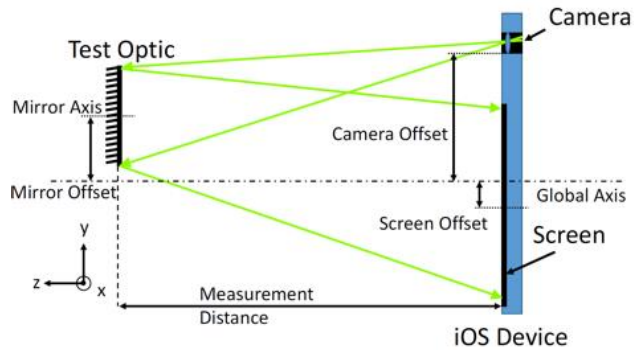

Fig. 4. A schematic of the proposed instantaneous phase shifting deflectometry system using iPhone's camera and screen. [5]

To be able to reconstruct the test surface, our method requires at least 6 data sets, during each measurement – phase shifting interferometry (PSI) mandates at least three data sets (e.g., having phase differences of 0, $\pi/3$ and $2\pi/3$ [10]) while slope based metrology methods such as deflectometry need double the amount of measured data (one set for each orthogonal direction). For our system, we multiplex the phase shifted information in a single display pattern and create an instantaneous measurement. To do this conceptually, two main ideas are used. First, the information corresponding to the three-step phase change is encoded using different colors (such as the Red, Green and Blue channels) of the display. Secondly, a large number of fringes in both the x and y directions are displayed on the screen simultaneously, which acts as a carrier frequency in the image (similar to the spatial frequency carrier interferometry). By combining these two concepts, we can multiplex six separate pieces of information corresponding to the three phase shifts in the two orthogonal directions necessary for an instantaneous phase shifted deflectometry measurement [5].

The camera's three color channels are read out separately to obtain three sets of data, corresponding to the three phase shifts required. In order to de-multiplex the combined x and y information, we make use of the properties of Fourier transforms. By applying a Fourier transform to each phase shifted image, we can convert the spatial domain data to a spatial-frequency domain, resulting in distinct peaks being observed at the locations corresponding to the carrier frequencies of the display fringes in the x and y directions. Hence, we split the multiplexed image into two separate images by applying a mask in the Fourier domain [5]. Naturally, an inverse Fourier transform is applied to the separated data and the one directional fringe patterns that made up the input image can then be reconstructed. In summary, from the single input image alone, we are able to obtain six unique outputs that comprise the three phase shifts in the two orthogonal directions required to reconstruct the test surface. This gives our system the distinctive capability of a temporal dynamic range that is non-existent in most metrology systems.

Once the one dimensional fringes are obtained, it is straightforward to use conventional deflectometry data processing algorithms to obtain the test surface. In our system, we used the following procedure for obtaining the reconstructed surface from fringes:

1. Apply a three phase step algorithm to each direction. This gives us four data arrays: two wrapped phases and their modulation - one in x and one in the y direction.
2. Unwrap the phases and convert them to slope data using the deflectometry system geometry parameters.
3. Integrate the slope data to obtain the reconstructed surface.

In the experimental verification set-up, a deformable mirror was used to generate time varying surface shapes that are measured in real-time with the instantaneous deflectometry system. We present the results of one of these measurements in Fig. 5.

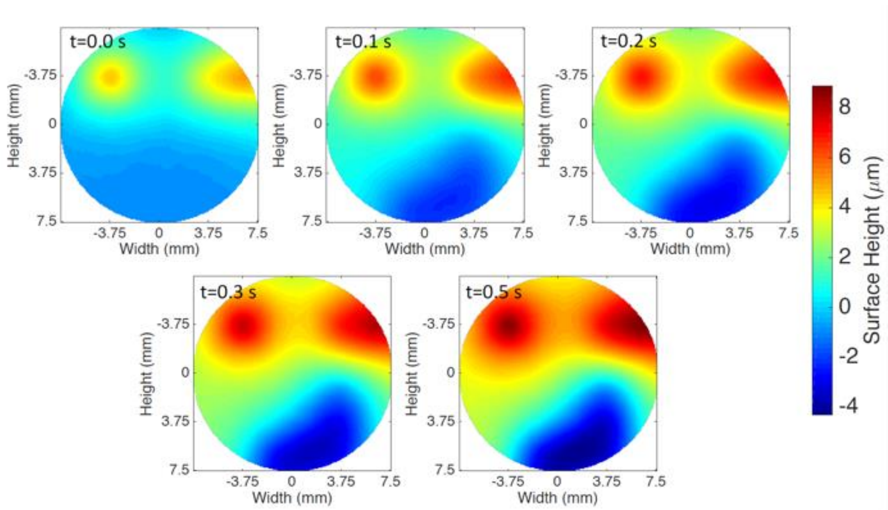

Fig. 5. Measured surface evolution (as a function of time) of the deformable mirror, where a set of actuators are moving linearly together from lower voltage to higher voltage.

We have made several other measurements and verified their results by cross-checking with both conventional phase shifting deflectometry as well as a commercial interferometer. The error between all three methods is of the order of 30 nm RMS, when measuring surface features with about 2 μm PV [5]. This level of agreement demonstrates that the instantaneous phase shifting deflectometry method is an accurate tool, especially considering an off-the-shelf iOS device based hardware setup. It is worth mentioning that our current iPhone system has a temporal bandwidth of the order of 10 Hz. The major limiting factors include efficient/low-noise image acquisition and iPhone hardware / software based limitations.

4. SURFACE RECONSTRUCTION FOR DYNAMIC METROLOGY

A modal deflectometry data processing methodology was developed, which utilizes orthonormal vector polynomials that can be defined as the gradients of a scalar function. These polynomials are used to modally fit measured slope data. If the coefficients of the vector polynomial fit can be straightforwardly converted to the coefficients of the corresponding scalar polynomial basis, the test surface can easily be reconstructed. We chose two-dimensional Chebyshev polynomials (called *F* polynomials henceforth) as the scalar basis. The vector or gradient basis can simply be constructed by taking the gradient of the scalar basis and re-normalizing it. This vector basis was named as the ***G*** polynomials. The mathematical form of this set can be written as

$$\vec{G}_j(x,y)=\vec{G}_n^m(x,y)=\nabla F_n^m(x,y)=\frac{\partial}{\partial x}F_n^m(x,y)\hat{i}+\frac{\partial}{\partial y}F_n^m(x,y)\hat{j}=T_n(y)T_m'(x)\hat{i}+T_m(x)T_n'(y)\hat{j} \qquad (1),$$

where T_n and T_m are the one-dimensional Chebyshev polynomials that make up the 2D basis set (i.e., *F* polynomials).

One of the most interesting aspects of this polynomial basis is that it can be expressed in a relatively easy, recursive form. This is usually not the case with gradient or vector polynomial basis sets. This unique capability allows us to easily and efficiently generate up to hundreds of thousands of polynomial terms. Clearly, this is a significant achievement in the context of precision freeform optics, where it is critical to accurately represent mid-to-high spatial frequency surface figure contents.

For a modal based fit, this can only be achieved if the basis set has a capability to have terms generated till hundreds, if not thousands of polynomials. The proposed data processing system has also been meticulously streamlined to be computationally efficient – a quality inherently difficult to achieve for most modal based fitting methods. As an example, using a typical desktop computer, one can generate up to 30,000 ***G*** polynomial terms in about 10 minutes.

Once the measured surface has been expressed as a function of some *N* number of ***G*** polynomials, we can obtain the coefficients of the scalar (*F*) basis by a simple one-to-one correlation (i.e., The vector polynomial coefficients are exactly the same as the scalar polynomial coefficients.) These coefficients can then be used to reconstruct the surface using the principle:

$$S=\sum_{k=1}^{N}a_kF_k \qquad (2),$$

where S is the reconstructed surface and a_k are the coefficients of expansion.

Analysis based on using our proposed method to reconstruct the test surface from simulated and real data shows our modal method to be highly accurate (in terms of the overall fit as well as mid-to-high spatial frequency representation of the surface) compared to the standard Southwell integration method [11], which is a popular surface reconstruction technique for deflectometry.

Another valuable property of the modal method is observed when measuring surfaces with obscurations. For deflectometry, often markers or fiducials are put on the surface of the test optic for an imaging distortion correction. If such a surface is reconstructed with a Southwell type zonal approach, it results in local errors, especially in the regions in the vicinity of the fiducial. Our proposed method is able to reconstruct the surface with a higher accuracy, partly owing to the fact that since it is a modal approach, it takes an overall view of the whole data, rather than focusing on sub-regions at a time.

For one of the simulations, a test surface with 5 fiducials on it was modeled. The modal method (using 2000 polynomial terms) gave a fit that had a residual error about 8 times smaller than the corresponding residual error from a Southwell approach. The surface maps from this simulation are shown in Fig. 6. The RMS of the ideal surface in Fig. 6 is

93.85 µm. The residual RMS error for the Southwell map in Fig. 6(b) is 5.96 µm (or 6.35% relative to the RMS of the ideal surface), whereas that for the modal fit in Fig. 6(c) is 0.76 µm (or 0.81% error).

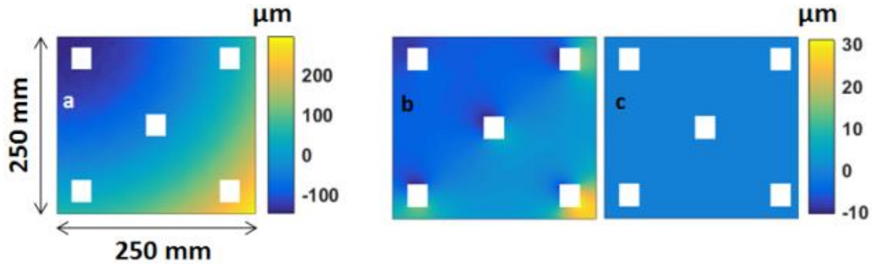

Fig. 6. (a) Simulated ideal surface data with 5 fiducial masks. (b) Southwell and (c) modal residual error maps (differences between the reconstructed surface map and the simulated ideal map).

In summation, the proposed modal data processing method supports the aim of high spatial resolution deflectometry by providing a key to improving accuracy and precision of the metrology system. The accuracy of the reconstruction, combined with the ability to represent very high-resolution surface maps ensures that the data processing techniques are valid for all stages of dynamic measurements. Furthermore, it reduces/removes the limitations on testing in the presence of obscurations and fiducials, as well being adaptable to various aperture types.

5. CONCLUSIONS

Dynamic metrology is a vital tool for measurement of precision freeform optics. By allowing an extended dynamic range, it pushes the boundaries on conventional freeform optics manufacturing and testing approaches. We have introduced two dynamic measurement concepts. The multiplexed deflectometry approach changes the temporal aspect of a conventional metrology by making an instantaneous phase shifting measurement demonstrated on a deformable mirror that varies with time. The second adaptable nulling method changes the spatial properties of a customized null component by introducing a deformable mirror controlled by the output from an SPGD search algorithm. Also provided is an overview of a high resolution slope data processing method that has the capability to support these concepts and technologies. This methodology modally fits measured slope data using sufficient terms to fully reconstruct the surface shape with mid-to-high spatial frequency contents.

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