Simulation and experimental results of sub-aperture, transmitted wavefront measurements of a window using a time-delayed source

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ABSTRACT

It is often desirable to measure an optical component whose aperture exceeds the capacity of the measurement device. However, stitching of sub-aperture measurement data in to a single measurement of an optical component is a challenging problem since mechanical motions of the test component relative to the reference surface of an interferometer can not be made with interferometric accuracy. Even more challenging than the need to compensate for rigid body motion between the sub-aperture measurements is the need to account for imperfections in the reference surface itself. In this paper we show, both in simulation and experimentally, how the use of a time-delayed source (TDS) simplifies the stitching of transmitted wavefront measurements from domes and windows. This is accomplished by making it possible to obtain phase-shifted interferometric measurements using only the light reflected by two surfaces from a dome or window without the use of a reference surface.

Keywords: Interferometry, stitching, simulation, transmitted wavefront, dome, window

1. INTRODUCTION

The time-delayed source (TDS) is a tool that has been developed for interferometric measurements of the transmitted wavefront of dome and window like optics1. One of the advantages of using a TDS based interferometer is that most of the system is common path and insensitive to environmental effects and alignment errors. Another significant advantage of the TDS is that a reference surface is not required for the measurements. This means that a property of the unit under test (UUT) is being directly measured instead of a property of the UUT with respect to a reference. Because of this, stitching of sub-aperture data requires placing the measured data in the correct location and removing piston terms between sub-apertures.

Before the interferometer was built, a system level software model was constructed in ASAP™. This model was used to perform a sensitivity analysis and a Monte Carlo simulation. This was used to set tolerances for the interferometer to ensure that the desired uncertainty was met. A TDS and interferometer were constructed and the environmental insensitivity demonstrated. Finally, sub-aperture data was stitched and the error was characterized. These results show how the robust nature of a TDS based interferometer simplifies sub-aperture stitching of dome and window like optics.

2. TIME-DELAYED SOURCE

A TDS based interferometer is, in fact, a pair of interferometers in series. This is done so that fringes can be obtained from a short coherence length source even when the optical path between the two interfering beams is greater than the coherence length. Figure 1 shows a schematic layout of a TDS. The light from a short coherence length source, such as a Superluminescent LED is used as the source for a Twyman-Green interferometer. The path lengths in each arm (L1 and L2) are different. In most cases, the difference in path lengths will be much greater than the coherence length of the source. If the output of the TDS is used as the input for another interferometer, one will see fringes only if the path lengths in the second interferometer are unequal by nearly the same amount as the difference in the TDS arms. In practice, one would adjust the path difference in the TDS to match the component being tested. This means that it is possible to obtain fringes from a thick part without having to use a long coherence length source. Two advantages of this approach are that it is not sensitive to stray reflections from surfaces in the interferometer and it is possible to phase shift the fringes by adjusting the path length in one arm of the TDS.

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Figure 1. Schematic diagram of a time-delayed source. Light from a short-coherence source is collimated and then directed to a beam splitter. Mirrors are used to return both the transmitted and reflected light through the fourth side of the beam splitter. Light from the two paths encounters a different time delay.

While short coherence length sources have been used with several types of interferometers\(^2,3,4\), there are additional advantages for stitching when a window is tested without a reference flat. Figure 2 shows a basic system for accomplishing this. The light from the TDS is directed to a beamsplitter. In this case, it is the reflected light that is of interest. This light is then collimated and is incident on the UUT. Light reflected from each surface is directed back into the interferometer, passes through the beamsplitter and is imaged onto a CCD (camera). When the TDS is adjusted so that the difference in path lengths is twice the thickness of the UUT multiplied by its index of refraction, fringes will be observed.

Figure 2. Basic interferometer for testing windows. The output of the TDS serves as the input for this interferometer. In this configuration, fringes will be observed when the path length difference between the two arms of the TDS matches the path length through the UUT. The fringes will record the thickness of the UUT multiplied by the local index of refraction.

The fringes that are observed are solely a property of the part. They are a direct measurement of the optical thickness of the UUT as a function of position. This is the data needed for sub-aperture finishing of the part, or one can easily calculate the transmitted wavefront from this data. This means that there is no reference surface that can contribute to
the uncertainty of the measurement. It also means that once the light leaves the TDS, everything except the material between the surfaces of the UUT is common path. It is the absence of a reference and the common path nature of the interferometer that make it ideally suited for stitching sub-aperture data.

3. SIMULATIONS

Before an interferometer was built, it was necessary to determine the required tolerances. To accomplish this, an interferometer was modeled in ASAP\textsuperscript{TM} and a sensitivity analysis was performed on a simulated UUT. Once this was complete, a Monte-Carlo simulation was conducted to determine the level of uncertainty we could expect from our interferometer.

The interferometer design shown in Figure 2 was used. In addition to the optics shown, there was an additional wavefront matching module that was required because the UUT was not a flat window. The wavefront matching module is beyond the scope of this paper. The simulated UUT had a small amount of power and wedge as well as two localized defects to simulate high spatial frequency errors. Figure 3 shows a simulated fringe pattern for the UUT. In addition to the fringes, the optical path difference (OPD) was directly simulated. This was used for the tolerance analysis which means that phase shifting errors were not included in the uncertainty calculations.

![Figure 3. Simulated fringe pattern for the UUT used in the sensitivity analysis. The curves below and to the right of the image are cross sections of the fringe pattern. The spot at the nine o’clock position is a small depression on one side of the UUT. The spot at twelve o’clock is a small bump on the other side of the UUT.](image)

For the sensitivity analysis, the same tolerances were used on each surface. The tolerance on power was set to five fringes at 633nm, the irregularity tolerance was one fringe at 633nm, the tilt tolerance was three arcminutes, and the spacing tolerance was 0.1mm. Each doublet also had a total indicated run out (TIR) tolerance of 10μm and a decenter tolerance of 0.1mm. Each tolerance was varied individually and set to its extreme values (plus and minus). The difference between the simulated OPD for a perfect interferometer was subtracted from the OPD for the perturbed interferometer. The peak to valley error was found for each tolerance. Since not all the errors were symmetrical about the nominal configuration, the largest error was selected. These peak to valley errors are listed in table 1. All of the errors listed are in nanometers.

For each simulations, three compensators were used. The first was that the UUT was aligned to the beam leaving the interferometer. This is comparable to adjusting a flat in tip and tilt when aligning it to a conventional interferometer. The second compensator was the position of the image on the CCD. Some of the errors can cause the image to shift on the CCD. Since the absolute location of the image was not critical, this variation was removed. The final compensator was magnification. Since the magnification can change slightly, this was also removed, but there was no compensator for anamorphic magnification. Certain tolerances were not included because the alignment plan removes them from the
system. Finally, it should be noted, that all of the tolerances listed may not be present in the final system. A detailed mechanical design will determine which ones may not be present and if any have been missed. The initial goal for the experimental system was to have a peak to valley measurement uncertainty of 15nm and an RMS measurement uncertainty of 3nm. Given the assumptions built into the sensitivity analysis, the peak to valley error if all of the errors are added linearly is 5.9nm. If they are root-sum-squared, the total is 1.7nm.

Because the interferometer is common path, the major sources of error are mapping and retrace error. Each pixel on the sensor is mapped to a particular location on the UUT. When there are fabrication or assembly tolerances in the interferometer, the exact mapping of the sensor onto the UUT has some uncertainty. This means that the measured OPD is slightly stretched or warped with respect to the ideal measurement. While it depends on the magnification and the wavefront matching optics, the mapping errors can often have sub-pixel magnitudes. The uncertainty that mapping error adds to the measurement is a function of the local slope of the OPD.

Retrace error arises when a ray that goes through the UUT in double pass does not reverse its direction and retrace its path on the second pass. This error is also dependent on the local slope of the OPD. Figure 4 shows the difference between the simulated OPD for an ideal interferometer and the simulated OPD for an interferometer where each parameter was randomly selected within the range of the tolerances. The difference scale is in nanometers. In Figure 4, the areas of localized OPD error are clearly seen. This is because these areas have higher slope and result in larger uncertainty.

![Figure 4](image.png)

Figure 4. Simulated OPD difference between an ideal interferometer and a perturbed interferometer. The scale is in nanometers.

Because these errors drive the peak to valley calculation but have little impact on the RMS uncertainty, they were removed for the Monte-Carlo simulation. A total of 110 simulations were performed for the Monte-Carlo simulation. Each value for each parameter was selected from the tolerance range with a uniform probability density function.

<table>
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<th>Power</th>
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<th>Spacing</th>
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<th>Lens Decenter</th>
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Table 1. Simulated peak to valley errors from the sensitivity analysis. All errors are reported in nanometers.
Figure 5. Simulated errors from the Monte-Carlo analysis. The mean value for the RMS errors is 0.18nm and the standard deviation is 0.12nm. The mean peak to valley error is 0.61nm, and the standard deviation is 0.36nm.

The peak to valley and RMS difference in OPD was calculated for each simulation. Figure 5 shows histograms for the peak to valley errors and the RMS errors. The 15nm peak to valley goal is nearly 40 standard deviations away from the mean peak to valley error. An RMS error of 3nm is over 20 standard deviations from mean RMS error. Based on this, the tolerances could be reduced and the uncertainty would still be below the goal. Because of these results, an experimental interferometer was built with off the shelf optics.

4. ENVIRONMENTAL INSENSITIVITY EXPERIMENTAL RESULTS

Because the interferometer is all common path except between the surfaces of the UUT, it is highly insensitive to environmental perturbations. In order to demonstrate this, a measurement was made of a window in a benign environment and then the measurement was repeated with a significant environmental stress added to the system. For this experiment, a heat gun was blown across the optical path in the interferometer. Figure 6a shows the measured fringe pattern without the heat gun and figure 6b shows the image with the heat gun present. Clearly there is little difference between the two. A phase shifted data set was acquired under each condition and the difference was calculated. When the extreme edges were excluded because the high slope results in phase shifting errors, the RMS error between the two measurements was 26nm. This should be compared to the basic repeatability of this experimental system which has an RMS repeatability error of approximately 18nm.

Based on the common path nature of the interferometer, one might expect that there should be no additional error. The most likely source of error is mapping error due to the highly turbulent air flowing through the optical path. When one observed the image of the fringes with the heat gun, they moved slightly. There was perceptible motion in the image of the fringe pattern that was comparable to seeing in a telescope that is due to atmospheric turbulence. In the interferometer, the effect was subtle. What was happening was the mapping of any given pixel onto the UUT was a function of the turbulent air in the optical path. This was why there was some error even though the system was common path. When no special effort was made to control air currents around the interferometer, no motion in the fringes was seen.
Figure 6. Measured fringe patterns from a window. (a) Measured fringe pattern under benign environmental conditions. (b) Measured fringe pattern when a heat gun was blown directly through the optical path.

5. EXPERIMENTALLY STITCHED DATA

Because a TDS based interferometer measures an attribute of the part and not the part with respect to a reference surface, it should be straightforward to stitch sub-aperture measurements. Unlike other approaches\(^5\), stitching sub-aperture data for windows and domes with a TDS based interferometer does not require as many correction factors. This is because the reference does not have to be removed from the data and small alignment errors do result in tilt and power in each sub-aperture which also needs to be removed. This means that one must calculate where each pixel in a sub-aperture belongs in the stitched data set. It is also necessary to remove a piston term between each sub-aperture, but no further processing is required to stitch the data. In order to demonstrate this, the window used to generate the data shown in figure 6 was scanned and the data stitched.

The interferometer used to measure the window shown in figure 6 was reconfigured to measure a smaller section of the window. The window was mounted on a rotation stage so that the part could be measured as it is revolved. Phase shifted data was collected every 30 degrees around the part. The center of rotation of the part was determined and each set of phase data was positioned so that the rigid body motion of the UUT was removed. This involved a simple rotation and shift of the data sets with respect to each other. Because phase unwrapping algorithms do not keep track of absolute phase\(^6\), there was a constant phase term (i.e. piston) that had to be subtracted from each sub-aperture. These terms had to be subtracted in order to form the final data set.

Typically, one removes errors from stitched data sets by distributing errors across the part and minimizing the RMS error. This can be done because most stitched sub-aperture sets from a closed data set. In other words, one could start by aligning the second data set to the first, the third to the second, etc. The last data set, however, needs to be aligned to the next to the last and the first data sets. The misalignment between the first and last data sets is an indication of the errors in the stitching process. Because these errors typically exist, they are distributed over the stitched data to minimize the RMS error.

Because of the common path nature of a TDS based interferometer, it is not necessary to do this. Each data point in each sub-aperture is a measurement of the phase of the UUT at that point. As long as one knows how the pixels on the CCD are mapped onto the UUT, the phase data can be properly placed. This is possible because the measurements in question are direct measurements of the part, and not the part with respect to a reference.

To position each sub-aperture requires a simple transformation of coordinates. To remove the piston, the average difference between data set one and data set two was calculated in the region of overlap. This value was then subtracted
from data set two to finish stitching data set two to data set one. The process was then repeated for data sets two and three, three and four, etc. This process treats a closed data set as an open one.

By keeping track of the piston terms that were subtracted out at each step, the piston term between the first and last data sets was calculated. The ideal piston term to align the first and last data sets can be directly calculated by starting the stitching process in the reverse order. When this is done, the ideal piston term that results in the minimum error between the first and last data sets is obtained. For our measured, stitched data, the difference between the calculated piston and the ideal piston was 12nm. To put this in context, the RMS difference between two measurements of the same sub-aperture taken without moving the UUT was 24nm. Also, the 12nm error can be compared to the measured RMS error in the UUT which was over 4,800nm. Figure 7 shows the stitched phase data. Each sub-aperture covered slightly less than one radius of the part. Because of this, the center of the part was not measured. Also, the slope of the optical thickness of the part at the edge is steep. This is why some of the data has dropped out near the edge.

![Stitched phase data](image)

Figure 7. Stitched phase data. A total of twelve sub-aperture measurements are included in this data set. This data set was treated as an open set even though it is closed. The error between the first and last sub-apertures because of this was 12nm.

### 6. CONCLUSION

The use of a TDS based interferometer has been described. A more detailed description of the TDS is published in these proceedings under the title, “Time-delayed source and interferometric measurement of domes and windows.” One of the key properties of a TDS based interferometer is that everything in the interferometer except the UUT is common path. This means that the tolerances on the components used to build the interferometer do not need to be tight. The tolerance analysis presented demonstrates this. Another benefit to the common path nature of a TDS based interferometer is that many types of environmental changes do not effect the measurement. This was demonstrated by recording phase shifted data with and without a heat gun blowing through the optical path.

A second key property of a TDS based interferometer is that it measures a property of the part and not of the part with respect to a reference. This makes stitching of sub-aperture data straight forward. All that is required is that one knows how each measured phase data point is mapped onto the UUT. This allows one to directly calculate all of the terms that
are need to stitch the sub-apertures together. The measurements presented show that one can treat a closed surface as an open one and demonstrate that the stitching error is less than the repeatability error.

REFERENCES