ABSTRACT

Measurement of the transmitted wavefront of domes and windows is a long-standing problem. One may use a large return sphere and measure the interference cavity without the dome present and again with the dome present. The difference between the two measurements is a double-pass measurement of the transmitted wavefront of the dome. Even so, the long coherence length of the source results in many extraneous fringe patterns. Windows may be tested by using a collimated source and return flat. A time-delayed source (TDS) having a short-coherence length is used to obtain a single interference pattern due only to interference of light reflected by the two surfaces of a dome or window. Standard phase-shifting algorithms may be used with the TDS to measure the optical thickness of a dome or window without errors due to multiple reflections. Since most of the interferometer is common-path, environmental sensitivity is reduced and alignment is straightforward compared to typical interferometers. Finally, since there is no reference surface, stitching of sub-aperture measurements is simplified.

Keywords: Dome, window, time-delay, short coherence, phase-shift, stitching, multiple reflections, common path

1. INTRODUCTION

Measurement of the transmitted wavefront of domes and windows is a long-standing problem. The common goal is to fabricate better and more complex domes and windows, faster and less expensively through the use of deterministic fabrication processes. All deterministic fabrication processes require measurement data with low measurement uncertainty and sufficient sampling that is easy to obtain in a manufacturing environment. Hemispherical domes and planar windows are two examples of constant-thickness optical components that present challenges to measurement with standard phase-shifting interferometric approaches.

2. BACKGROUND

The classic method of testing the concentricity of a spherical shell is illustrated in Fig. 1 below. A source with a coherence length greater than twice the optical thickness of the dome is required. Fizeau fringes are due to light reflected from the inner and outer dome surfaces. For a perfect shell the radius of curvature of the outer surface is equal to the sum of the radius of curvature of the inner surface and the thickness of the dome and a null fringe pattern will result. If the centers of curvature of the two surfaces are laterally displaced straight line fringes will result due to the wedge between the surfaces. If the radii are mismatched than circular fringes will result due to the power difference.

It is possible to analyze a static fringe pattern; however, this type of analysis is not as accurate or robust as phase-shifting methods. Most phase-shifting interferometers modulate the phase by moving a reference surface, but that is not possible in this rather simple configuration. An alternative approach is to vary the wavelength of the source so as to modulate the phase. Such methods can work; however, they depend upon the use of a sufficiently coherent source. Unfortunately the ghost reflections from a source will also be at least partially coherent with the primary reflections. It only takes a weak ghost reflection from the test or reference surface that is coherent to produce significant errors in the measured phase.

*bill.kuhn@wpkuhn.com; phone 1 520 867-8632
Another approach is to use a modern phase-shifting Fizeau interferometer as illustrated in Fig. 2 below for the testing of a plane parallel window. Two measurements are performed of the Fizeau cavity formed by the interferometer transmission flat (i.e. reference surface) and return flat, one with and one without the window present. The difference between the two measurements is the transmitted wavefront of the window in double-pass. A spherical dome can be tested in a similar manner using a transmission sphere and return sphere instead of a transmission flat and return flat.

Using the Fizeau interferometer does require good alignment of the return flat to minimize retrace errors. Ghost reflections can often be suppressed by tilting of the window. However, tilting of the window contributes to retrace error. Although in the testing of windows the air path can be made small to reduce environmental effects the parts must be handled with care. The problems are compounded when testing a dome where a part under test must be fit inside a small space.
There is a difference between the measured optical-path difference in the spherical shell concentricity test and a test using a spherical return mirror. Fig. 3 represents a small section of a window or dome having index of refraction \( n \). In the transmitted-wavefront test (double-pass) shown in Fig. 2, the optical path difference between cross-section B and A is

\[
\text{OPD} = 2nL_2 - 2(nL_1 + \Delta L) = 2(nL_2 - nL_1 - \Delta L) = 2(n\Delta L - \Delta L) = 2(n-1)\Delta L(x, y). \tag{1}
\]

In the concentricity test (Fig. 1), the optical path difference between cross-section B and A is

\[
\text{OPD} = 2nL_2 - 2nL_1 = 2n\Delta L(x, y). \tag{2}
\]

The concentricity test has greater sensitivity than the transmitted wavefront test by a factor of \( n/(n-1) \). However, both directly measure the variation of the optical thickness which is the parameter of interest and are effectively transmitted wavefront measurement techniques.

A recently introduced interferometer, the Zygo MST, performs Fourier Transform Phase Shifting interferometry to measure multiple surfaces encountered when measuring a plane window. The instrument is capable of measuring both surfaces and material homogeneity. However the instrument is based upon a Fizeau interferometer with its reference surface and requires vibration isolation.

The current and historic methods have both desirable and undesirable properties. The simplest technique — Fizeau fringes from the inner and outer dome surface — is easy to align and insensitive to the environment, but has limited accuracy. The more advanced instruments are accurate and robust but require careful alignment and are sensitive to the environment.

3. TIME-DELAYED SOURCE

A schematic time-delayed source (TDS) is shown in Fig. 4. A short-coherence length source is used. The light is collimated and then directed at a beam splitter. A portion of the light is reflected and a portion transmitted, both paths have a mirror to reflect the light back to the beam splitter. A portion of each beam reflected by the mirror exits the fourth side of the beam splitter; however, there is a delay between the reflections from the two paths due to the different lengths of the two paths.

The coherence properties of the TDS are essential to its use. Consider first the coherence properties of the source. Consider the setup shown in Fig. 4 and that reflections from Mirror 1 and Mirror 2 are tilted with respect to each other such that a fringe pattern is observed on a screen at the Output. Ignoring ghosts, there are two beams of equal irradiance and the visibility of the fringes produced would be one for a short coherence source only if the optical path length difference between the two paths is zero and all the reflection coefficients are equal. As the path length difference is changed from zero to a small distance \( L_C \) (source coherence length) the fringe visibility will rapidly approach zero as shown by the solid line in Fig. 5.
Fig. 4. Schematic diagram of a TDS. 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.

Fig. 5. Fringe visibility using a TDS. Solid line is fringe visibility for a short coherence source. The dotted lines are fringe visibility for a short coherence source after passing through the optical system of Fig. 3 with an optical delay of $L_D$.

Repeating the fringe visibility experiment using the output of a TDS as the source will produce the dotted lines in Fig. 5. The fringe visibility is at most $\frac{1}{2}$, but there are two peaks separated by the delay length ($L_D$) between the two paths. The maximum visibility is $\frac{1}{2}$ instead of 1 because there is now light from four paths – each path of the TDS paired with reflections from the two paths in the tool for measuring fringe visibility. If the distance $L_D$ in the TDS is set to match the path difference in the measurement tool light from two of the four paths will interfere.

4. BENEFITS

The output of a TDS may be used in the concentricity test of a spherical shell shown in Fig. 1. If this is done, the fringe visibility will be at most $\frac{1}{2}$, which is less than what one could obtain with a helium-neon laser. However, if a short-coherence source, such as a super-luminescent photodiode is used with a coherence length of perhaps 1 mm or less then ghost reflections from the spherical shell will not contribute to the interference pattern.
Also, phase-shifting of the interference pattern may be simply accomplished by moving one of the mirrors in the TDS using for example a piezo-electric transducer. Optical path length matching may be accomplished by moving one of the mirrors in the TDS (i.e. an optical delay line). The absolute optical thickness of an optic can be measured directly by measuring the optical delay. If a physical thickness is known for the part then the index of refraction can also be measured.

Since the setup is common-path except for the interior of the part being tested, environmental effects such as vibration and air turbulence have no practical effect on the measured data. Alignment is also quite easy since fringes can be obtained even when the center of curvature of the spherical shell is not aligned accurately to the pinhole.

5. SUB-APERTURE TESTING

Full-aperture testing of large domes and windows is also a problem. There are practical limitations to testing a large numerical aperture dome as well as testing large windows. The environmental and alignment insensitivity present in a TDS approach for transmitted wavefront measurements are helpful when performing sub-aperture testing. This is especially true when the sub-aperture data is being “stitched” into a single measurement. The greatest benefit for stitching sub-aperture data is the absence of a reference surface.

Stitching of general test data from wavefront data is a challenging problem. The techniques must incorporate or solve for the reference surface5. However, since the TDS approach measures the transmitted wavefront directly, without the use of a reference surface stitching in this case is a much simpler proposition. Fundamentally all that is required is to correctly locate in a suitable coordinate system all of the measured data. This would be done using the motion axes and commanded positions. The only free parameter is a DC offset between the data sets. The DC offset is required because the interferometer is measuring difference data and has no absolute phase reference.

6. CONCLUSIONS

A TDS and its use for the testing of constant or near-constant thickness optics has been described. The two interfering beams are largely common-path resulting in greatly reduced environmental sensitivity for the measurement of spherical domes and windows. The instrument measures the variation in optical thickness of the part without the use of a reference optic. This will simplify alignment and should result in a relatively simple algorithm for stitching of sub-aperture data. Experimental results are published in these proceedings under the title “Simulation and experimental results of sub-aperture, transmitted wavefront measurements of a window using a time-delayed source”.

REFERENCES