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Tutorial

Practical aspects of modern interferometry for optical manufacturing quality control: Part 1

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Abstract

Modern phase shifting interferometers enable the manufacture of optical systems that drive the global economy. Semiconductor chips, solid-state cameras, cell phone cameras, infrared imaging systems, space based satellite imaging and DVD and Blu-Ray disks are all enabled by phase shifting interferometers. Theoretical treatments of data analysis and instrument design advance the technology but often are not helpful towards the practical use of interferometers. An understanding of the parameters that drive system performance is critical to produce useful results. Any interferometer will produce a data map and results; this paper reviews some of the key issues to minimize error sources in that data and provide a valid measurement.

Keywords: coherence; Fizeau; interferometer; reference surface; Twyman-Green.

1. Introduction

Interferometers are enabling tools in high-technology manufacturing. Semiconductor products, computers and cell phones would not exist without the application of several interferometer types. Blu-Ray disk players manufacturing requires interferometers for process control of diffraction-limited molded aspheric lenses to create high-quality home entertainment. Today, most optical imaging and illumination systems utilize interferometry for process control and performance optimization. Therefore, a practical understanding of interferometry, its application and sense of future direction is required in the field of optics. This paper will focus on those aspects in three parts. Part 1 will cover the history and basic descriptions of interferometer systems, part 2 metrology and data acquisition, and part 3 data analysis and future directions.

Interferometers are dimensional metrology systems. Interferometers measure phase of the interference pattern created between the part under test and the reference surface. Phase is then converted to distance [1]. In this paper, only interferometers that provide three-dimensional surface or wavefront maps will be discussed. The ideal interferometer will map the three-dimensional optical surface with no distortion (error) in height or position, regardless as to whether the surface is a flat, sphere or asphere. Furthermore, the ideal system would be robust against environmental influences such as vibration and temperature, and it would be very easy to use, never producing an error. Finally, all results would comply with international standards. Obviously no interferometer achieves this ideal, yet the goal of this paper is to provide the user some tools to achieve performance closer to the ideal.

Numerous interferometer configurations exist. The Twyman-Green and Fizeau interferometer types are most common and therefore will be discussed in detail. Other interferometer types will be mentioned. For further reading refer to references [2–4].

Data analysis is critical to interpreting the surface data. Analysis and the evaluation of measurement uncertainty are beyond the scope of this paper. Several international committees are focusing on the development and coordination of surface data analysis. For these topics refer to ISO and JCGM references, respectively [5, 6].

2. Brief history

Test plates were the interferometer of choice the first 70 years of the past century, and are still used in production today. Interference fringes, the intensity fluxuations created by light interference, between two closely spaced and matched optical surfaces, one of known quality, the other the unknown test part, are analyzed for power and deviation. In 1925, the Twyman-Green [7] interferometer was created for the testing of optical components. The original compensated Twyman-Green interferometer has equal optical path lengths for the test and reference arms, producing interference fringes with short coherence sources. The invention of the laser in the early 1960s enabled unequal path length interferometers including certain Twyman-Green configurations and a practical Fizeau [8] system introduced in the 1970s [9, 10]. The practical Fizeau was easy to set up, even by unskilled operators, produced reliable data and was flexible to accommodate many set-up configurations [11]. The Fizeau interferometer quickly became the configuration of choice.

Computer technology refined the analysis of fringe patterns. First, static-fringe data acquisition via fringe center location mimicked visual analysis [12]. Static-fringe analysis minimized subjective influences but produced only very low spatial frequency, or form data. In addition, static-fringe analysis results varied with interference fringe density. Higher density fringes increased system off-axis aberrations distorting the fringes and varying numbers of fringes acquired varying spatial frequencies in the acquired data changing the measurement conditions. Simply, the test conditions were not stable.

Phase shifting interferometry [13, 14] (PSI) integrated computers and fine mechanics with the interferometer data acquisition. PSI provides high-density data sets and is generally fast and easy to use, non-contact and produces reproducible and traceable results. As computerized PSI interferometers were introduced, the tremendous global demand for higher powered computers, solid state imaging systems and mobile computing systems drove the requirement for precision optics, and continues to drive the evolution of interferometers. Originally designed to only measure flats, spheres and conic optics, interferometers now measure aspheric surfaces [15–18]. Interferometer evolution has led to more robust systems, but also has increased the demand on operator knowledge to achieve the performance required for precision lens system testing. Listed in Table 1 are examples of markets, applications and measurements made by modern PSI interferometers.

3. Interferometer configurations

All interferometers have several common subsystems: illumination (lamp or laser), beamsplitter, reference surface, test part and imaging system (camera or visual). The configurations of these subsystems create various interferometer types, as described below. Of particular importance are the illuminator optical coherence, and the beamsplitter and reference surface configuration.

3.1. Illuminator optical coherence

Illuminator spatial and temporal coherence drive interferometer design. Spatial coherence refers to the correlation of the wavefront orthogonal to the direction of propagation. If the phase of the wavefront is the same, i.e., correlates across the wavefront, the beam is spatially coherent. Lasers typically have very high spatial coherence. Spatial coherence allows interference across a wavefront. The control of spatial coherence, decreasing it by design, is effective to localize interference affects. Furthermore, interference localization is critical to the operation of some types of interferometers, for instance, where interference fringes need to be localized to a single surface to eliminate secondary surface reflections [19]. These topics will be discussed in part 2 of this paper.

Temporal coherence refers to the correlation of the beam phase along the direction of propagation. Single mode lasers that emit a narrow band of wavelengths have high temporal coherence. High temporal coherence sources exhibit a long coherence length. Coherence length is the optical path difference over which high contrast fringes can be produced. It is easy to see that a light source with high temporal coherence enables the use of unequal path interferometers (discussed below) that require long coherence lengths.

At a fundamental level, the illuminator coherence determines the interferometer design options. Interferometers with unequal optical paths typically require laser sources. Illuminators with decreasing temporal or spatial coherence require interferometers with more equal paths, and a white light source demands the use of a compensated interferometer, meaning equal optical paths for all wavelengths that are present.

Table 1 Typical optical testing requirements.

	Size range (mm)	Measurement uncertainty (nm RMS)	Flat	Sphere	Asphere	System wavelength (nm)
Consumer						
Cell phone lenses	<3	30		✓	✓	550
Digital/DVR cameras	<100	30	✓	✓	✓	630
Optical heads	<5	20			✓	405
Industrial						
Machine vision systems	<100	30		✓	✓	630
Microscopes	<25	20		✓	✓	VIS
Scientific instruments	5–1000	5–100	✓	✓	✓	EUV–LWIR
Security						
Night vision	<150	30–100	✓	✓	✓	VIS–LWIR
Earth imaging satellites	300–1000	30–100	✓	✓	✓	UV–LWIR
Semi						
Imaging (UV-DUV)	<350	2–5	✓	✓	✓	EUV–300
Stage mirrors	<1000	10	✓			633
Medical						
Endo/Cysto/Colonoscopy	1–5	30		✓	✓	VIS
Contact/Intraocular lenses	8	20		✓	✓	VIS
R&D/Other						
Telescopes	<8400	30	✓	✓	✓	633
X-ray optics (Relec)	25–1000	2	✓		✓	633
Material homogeneity	<1000	10	✓			633

4. Types of interferometers: overview

4.1. Equal path interferometers

4.1.1. Compensated Twyman-Green Equal path interferometers produce fringes even with wide spectral bandwidth light sources, where multiple wavelengths are present. Before the invention of the laser these were the only interferometers that were practical to use in optical testing. Even today they have tremendous utility, but are mostly used as optical surface profilers utilizing coherent scanning interferometry [20, 21] not for optical surface form testing. Occasionally compensated Twyman-Green systems are required to test the transmitted wavefront where inadequate laser sources are available at the design wavelength.

The lower the coherence the more compensation is required. Before lasers equal optical path lengths needed to be maintained in both the test and reference arms, over the illumination bandwidth. To achieve equal optical path lengths optical dispersion in all the optics must be considered for all wavelengths transmitted by the interferometer. This is achieved by making the test and reference arms identical. Consider the beamsplitter as shown in Figure 1. The test arm path passes the beamsplitter thickness three times, the reference only once. To compensate for this a piece of glass equal in thickness and material to the beamsplitter is placed in the reference arm. Fortunately, this level of path equalization is rarely needed with current laser sources. If a focusing lens is placed in the test path, a focusing lens must also be placed in the reference path, greatly increasing the cost and complexity of the test.

Owing to these complexities, compensated Twyman-Green interferometers are no longer used to test surface optical surfaces, and very rarely used for system testing. For surface and system testing unequal path interferometers are far easier to build and use.

4.2. Unequal path interferometers

Unequal path interferometers are the workhorse of the optics industry. The invention of the laser in the early 1960s revolutionized interferometer design. With high spatial and temporal coherence, compensated interferometer designs were no longer required as interference is now easy to produce.

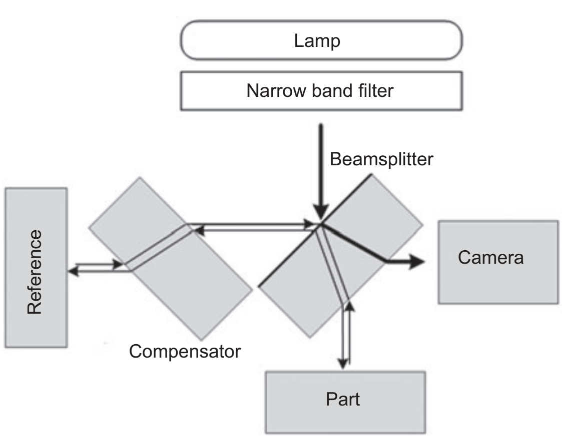

Figure 1 Compensated Twyman-Green interferometer.

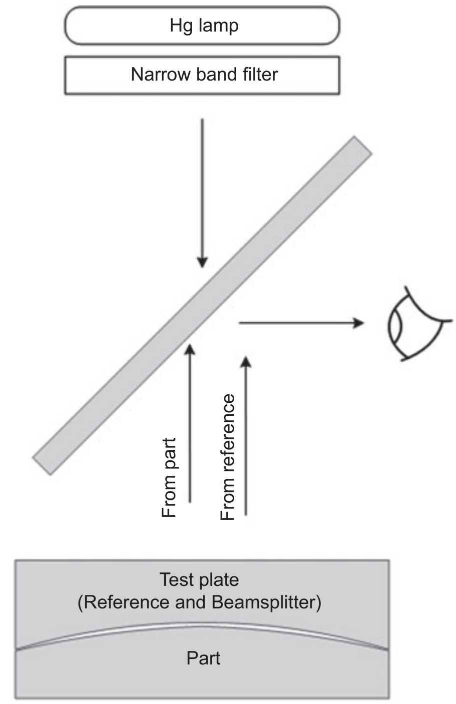

Figure 2 Test plate interferometer.

4.2.1. Test plates It is instructive to start with the precursor to modern interferometers, test plates (Figure 2). Test plates can be considered to be a Fizeau interferometer where the path difference is almost zero. This zero path difference creates a Fresnel interferometer where the test surface and reference surface are in physical contact. In this case, the reference surface is the test plate that has a known radius of curvature and surface irregularity (form). The part under test is manufactured to be an identical surface to the test plate. When placed on each other an air film floats the test plate over the part under test. When observed under filtered mercury vapor lamps interference fringes are observed. The test plate forms the reference wavefront; the measured wavefront is formed by the part under test. Only path differences of a few microns produce interference.

Test plate interferometers have many limitations. Test plate measurement can scratch the lens under test, and is not reproducible or traceable to a standard. Traceability is a problem especially when the test part is not mechanically stable and can bend by adhesion forces. Furthermore, an expensive library of test plates must be maintained and calibrated in all optical shops. Interferometers, where the test and reference are separated in space, eliminated most of these shortcomings, and the Fizeau interferometer is a natural extension to test plates.

4.2.2. Fizeau interferometer The Fizeau interferometer is the most widely used interferometer configuration for optical testing today. It was invented by M.H. Fizeau in the mid-19th century, and became a practical alternative after the invention of the laser. The practicality of the Fizeau configuration is found in its simplicity. The Fizeau interferometer is composed of an illumination optical path, the interferometer cavity and an imaging path.

Illumination must be both spatially and temporally coherent to accommodate the unequal path in the interferometer cavity. Therefore, laser sources are used. With these highly coherent sources not only does interference occur in the cavity but also secondary interference from optical surfaces, and dust and scratches (often called artifacts) can degrade the results. These artifacts can be minimized through design, super clean surfaces and new partial-coherence illuminator designs created to minimize these effects. This topic will be covered in part 2 of this paper.

The primary strength of the Fizeau interferometer is the combination beamsplitter-reference surface. By combining the beamsplitter and reference surface the Fizeau has no intervening optics in the test path to degrade the reference wavefront. Furthermore, when measuring a perfect spherical test optic the test and reference wavefront return along the same path. Thus, the Fizeau interferometer is a common path design where errors in the illumination and imaging systems produce second order errors. Therefore, the Fizeau interferometer measurement uncertainty is primarily dependent on the quality of the reference surface, a unique feature of Fizeau interferometers. The second order errors become important as the returning test wavefront deviates from spherical. This is particularly true with the measurement of aspheric surfaces.

Again, the Fizeau interferometer is similar to a test plate system with a large air gap. The large air gap allows an infinite number of radii of curvature to be measured with one

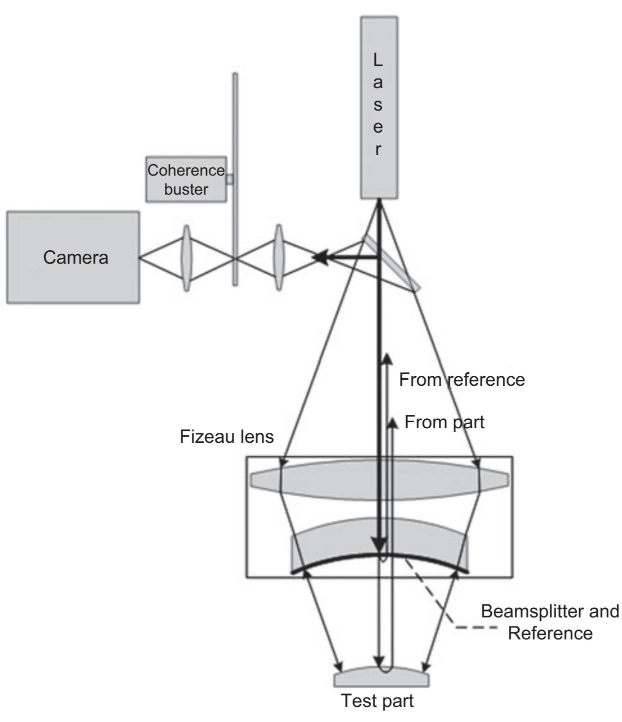

Figure 3 Fizeau interferometer.

reference surface (see Figure 3). A convex reference measures both concave and convex surfaces and a plano reference measures flat components. Thus, a Fizeau can replace a library of test plates with a small set of Fizeau lenses where each includes a reference surface. To accommodate a wide range of test radii, several Fizeau reference lenses might be required. Some examples of Fizeau lens selection charts are available from commercial manufacturers [22].

The interferometer cavity test part surface is imaged on a CCD camera to view the interference fringes and analyze the data for further processing. Variable magnification camera lenses, zoom and fixed magnification, are used to match the test part image to the camera imaging area. The laser source coherence again must be managed in the imaging system to minimize artifacts. Three approaches have been implemented in the commercial system. First, off-the-shelf zoom lenses are used in many systems. Commercial lenses are designed for operation with incoherent light. Therefore, with commercial zoom lenses a so-called ‘coherence buster’ creates spatially incoherent light, making commercial zoom lenses use possible. Many systems use either a custom-designed zoom lens or discrete imaging camera lenses of varying magnification. In these systems, great care must be exercised in the manufacture and maintenance of the system to eliminate dust from forming on the optics.

Fizeau interferometers are the most common type of interferometer used today, but they are not always the optimal configuration for a particular application.

4.2.3. Twyman-Green interferometer The Twyman-Green interferometer usage decreased after the invention of the laser, when laser Fizeau interferometers emerged. Even though, the Twyman-Green interferometer has great utility today. It is the only configuration that can be used with certain short coherence lasers, and has been shown to be useful for the measurement of aspheres [23, 24] and deformable mirrors [25], and enabling simultaneous phase measuring interferometry utilized for the measurement in high vibration and turbulent atmosphere environments [26], a subject to be covered in part 2 of this paper.

The Twyman-Green differs from a Fizeau as the beamsplitter and reference surfaces are separated. Yet, the illumination and imaging paths are fundamentally the same as a Fizeau. By separating the beamsplitter and reference surface, the optical path difference between the reference to beamsplitter path, and test to beamsplitter path, can be adjusted to accommodate shorter coherence illumination sources. This is important when optical system testing requires wavelengths not available with long coherence sources. Recent examples are the transmitted wavefront testing of Blu-Ray objective lenses [27] and semiconductor optical birefringence testing at 193 nm and 157 nm wavelengths [28]. In these instances, the use of the Twyman-Green was the best choice.

Optical component and system testing is similar to a Fizeau interferometer. In place of the Fizeau lens, a focusing lens creates a spherical test wavefront to measure a family of spherical surfaces and is also used for finite conjugate system testing. A collimated wavefront is used to measure plano test

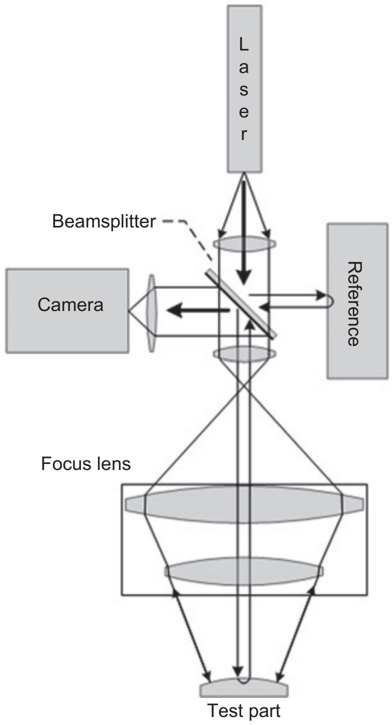

Figure 4 Non-compensated laser Twyman-Green interferometer.

parts. Commercially available test lenses and selection charts are available [29].

This powerful flexibility sacrifices common path operation and introduces errors not found in the Fizeau interferometer. First, the beamsplitter quality influences the test and reference paths differently. As shown in Figure 4, the test optic path wavefront is degraded by any beamsplitter flatness deviation times the square root of 2, due to the 45° angle of incidence. The multiple passes of the reference beam through the beamsplitter additionally degrades the reference wavefront. Optionally, a cube beamsplitter can be used to balance errors between the two arms, except where the beamsplitter is not symmetrical. Furthermore, the Twyman-Green focusing lens is located in the test path and its aberrations will degrade the measurement wavefront. Environmental variation such as temperature also will affect the optical paths differently causing the wavefront to vary. Therefore, environmental control and calibration are required when using a Twyman-Green interferometer, which will be addressed in part 2 of this paper.

4.3. Special purpose interferometers

4.3.1. Laser unequal path interferometer (LUPI) A clever implementation of the unequal path Twyman-Green is the LUPI. Invented in the early 1970s [30], it utilized the laser for long coherence and is typically constructed as a stand-alone module. A particularly interesting configuration is the ‘shack interferometer’, which requires only one precision component to test a large concave mirror [31].

4.3.2. Grazing incidence Grazing incidence interferometers can be of the Twyman-Green or Fizeau configuration. These systems are configured so that a nominally flat test part is illuminated at a steep angle. The grazing incidence angle causes the effective measurement wavelength to increase by the reciprocal of the cosine of the incidence angle.

Grazing incidence systems are used to measure surfaces that are not specular at normal incidence for the available wavelength. This enables that ground surfaces can be measured with an interferometer [32]. Likewise, the long effective wavelength enables surfaces with large flatness deviation to be measured [33]. Finally, long thin flats such as reference mirrors can be measured with a small aperture interferometer, but care must be taken to avoid errors due to diffraction as focus cannot be achieved across the entire test part simultaneously.

5. Optimizing performance

To achieve optimal performance in any interferometers part set-up, reference surface calibration, imaging focus and distortion, control of the illumination coherence, data analysis and filtering and other factors must be optimized. These topics will be covered in future additions of this paper for the Fizeau and Twyman-Green configurations.

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