The FizCam 2000 dynamic interferometer enables vibration insensitive measurement of plane parallel optics, remote cavities and large convex mirrors.

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Novel Interferometer Enables Challenging Measurements

Introduction

Dynamic interferometry is a standard technique for measuring optics, meter-class optics and optical systems in challenging environments. The method provides high out-of-plane resolution and repeatability even in the presence of significant vibration and air turbulence. A new dynamic interferometer utilizing a proprietary laser source and patented optical configuration has enabled wavefront measurements which until now have been difficult or impossible to complete with standard temporal phase-shifting systems. This article describes a short coherence Fizeau interferometer and its applications for measuring large telescope optics, general purpose optics, disk drive substrates and media, flat panel display components and lithography optics.

Vibration Insensitivity

In an interferometer, light reflecting from a test and reference surface combine to produce patterns of light and dark fringes called “interferograms.” By acquiring a series of interferograms and applying algorithms, the system extracts the shape of the test surface with sub-nanometer vertical resolution.

In a standard phase-shifting interferometer, the test or reference surface is mechanically shifted by nanometer-scale increments, and a frame of data is obtained after each shift. This acquisition method takes less than a second but is far from instantaneous, thus any vibration or air turbulence during the measurement will have a significant impact on the results. To overcome these problems, the entire system (interferometer, test optic and mounts) must be carefully coupled together and isolated from vibration and air turbulence. Isolation is possible, though cumbersome, for some applications; for others, such as measurement of large, convex optics, it can be prohibitively expensive or impossible.

In a “dynamic interferometer” all phase data is acquired simultaneously, more than 1000 times faster than a temporal phase-shifting interferometer. Such short acquisition time renders the system virtually immune to environmental noise. Vibration isolation is not required, enabling the instrument to be used in noisy environments such as clean rooms, production floors or environmental testing chambers. The system can even measure moving or resonating parts, such as spinning disk drive components, or large sheets of flat panel display glass which are highly susceptible to vibration.

Ability to Isolate Surfaces

In a standard Fizeau interferometer with a long coherence source, interference fringes will be generated between any parallel, reflective surfaces in the test path. For measuring many optical elements this poses no problem; however, when measuring transparent optics such as windows, prisms or glass disks, interference will occur between all of the reflective surfaces, resulting in complex interferograms from which it is difficult or impossible to determine the shape of the test surface. To isolate and measure the front surface, one must typically coat the back surface to eliminate its reflection, a time-consuming operation which is potentially detrimental to the optic.

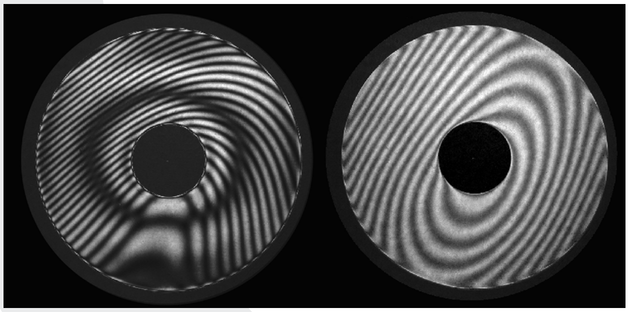

Figure 1. A glass disk imaged with a standard interferometer (left) and a FizCam 2000 dynamic interferometer (right).

Optical Metrology for a Dynamic World

To more readily isolate surfaces, the FizCam 2000 dynamic Fizeau interferometer utilizes a proprietary laser source and patented optical configuration with a coherence length of 300 microns. An “optical path matching” mechanism within the interferometer makes it possible to position this 300-micron range such that fringes will only occur between the desired surfaces. This feature makes it possible to measure plane parallel surfaces as close as 300 microns apart.

Figure 1 shows a 1 mm thick glass disk as imaged with a standard interferometer (left) and as imaged with 4D Technology’s FizCam 2000 dynamic Fizeau interferometer. The short coherence source eliminates fringes caused by the back surface, allowing the front surface to be accurately measured.

Figure 2 shows the configuration for measuring both surfaces and the pixel-by-pixel thickness of a transparent disk in a single measurement. The measurement process begins with adjusting light intensity and minimizing tip/tilt with respect to the reference flat, as with a standard interferometer. Next, the automatic path matching feature is used to locate all “coherence peaks,” which correspond to interference between each pair of reflecting surfaces. Figure 3 shows two peaks, corresponding to interference between the front surface and reference (A) and the back surface and reference (B). Peak A occurs at distance X. Peak B occurs at X + T*n, where n is the index of refraction of the disk.

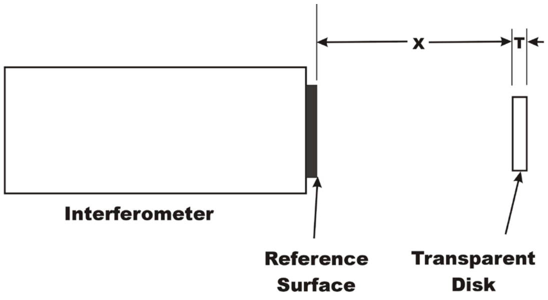

Figure 2. Test setup for measuring both surfaces and thickness of a transparent disk.

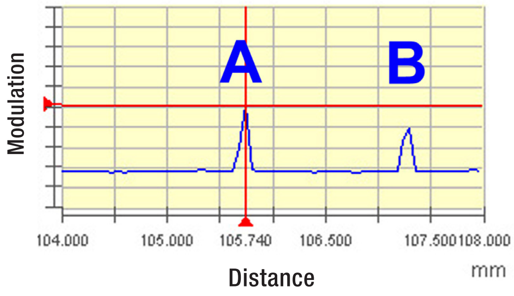

Figure 3. Path matching results for glass disk. X=105.7 mm, t=1 mm, n = 1.5.

Selecting peak A adjusts the path matching mechanism to produce fringes between the front surface and reference, with no additional fringes from the back surface. The front surface can now be measured without coating the back surface or other methods to suppress interference.

Selecting Peak B adjusts the path matching mechanism to produce fringes from the back surface and reference. A measurement can then be made of the back surface, through the disk. The resulting shape will include contributions from the back surface, front surface, and the glass itself. The back surface shape S2 can be found using the equation:

$$S2 = \frac{M2 + (n + 1)\,M1}{n}$$

Where:
M1 = measurement of front surface
M2 = measurement through the glass to the back surface
n = index of refraction of the disk material (assumed here to be a constant).

Figure 4 shows a direct measurement of a glass disk surface (left) as compared to the same surface measured through the disk using the method above (right). The through-glass data was flipped and aligned rotationally to the front data. The close comparison indicates the accuracy of the through-glass measurement approach.

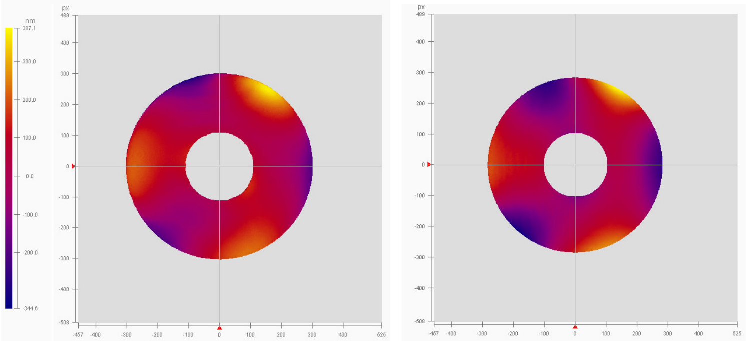

Figure 4. Direct measurement of one surface of a transparent disk (left) and a measurement of the same surface made through the disk (right).

The two measurements (front of glass and through-measurement of the back) can also be recombined to solve for pixel-by-pixel variation in disk thickness. The FizCam 2000 thereby enables measurement of both disk surfaces and disk thickness in a single measurement setup. The utility extends to other applications involving measurement of thin, transparent optics, including inspection of large glass substrates for flat panel displays. In some cases it also enables measurement of the individual surfaces of multi-component optical systems, prisms, etc.

Remote Cavity Measurements

The interferometric "cavity" is the distance between the reference and test surfaces. In a standard, temporal phase-shifting Fizeau interferometer, the reference must be a high quality transmission flat or sphere, which is translated by Piezo actuators to obtain the series of interferograms needed to extract the surface shape. The translation mechanism can be cumbersome as well as slow, particularly when using a very large reference optic.

In a dynamic interferometer the reference does not need to translate relative to the test surface. The reference can therefore be any surface in the test path, such as one end of a laser rod, the front of a glass disk, etc. These "remote cavities," consisting of two parallel surfaces which are not coupled to the interferometer, can be measured by the FizCam 2000.

To continue the example above, a transparent glass disk can be measured using the FizCam 2000 without a transmission flat, using the front surface of the disk as the reference instead. The automatic path matching mechanism would now locate one primary peak at a distance where the front and back surfaces interfere. The peak occurs at 1.5 mm, or T*n (Figure 5). The ability to measure remote cavities enables measurement of thickness variation even between surfaces that cannot be phase-shifted, such as the faces of a prism or the ends of a laser rod. A remotely located cavity (e.g., an optic positioned in an environmental chamber) can also be measured. In some cases one can measure the relative orientation between surfaces in a multi-surface optical element.

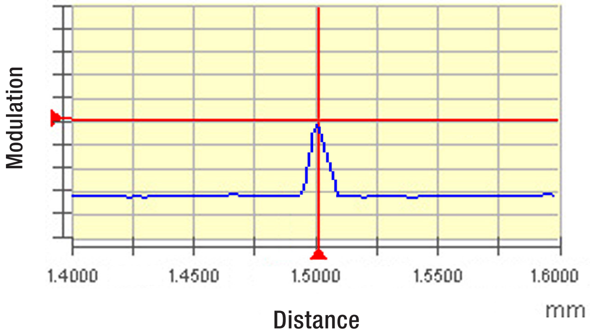

Figure 5. Path matching results for a transparent disk using the remote cavity method.

Large Optics

One critical application addressed by the FizCam 2000 is the measurement of the James Webb Space Telescope's (JWST) secondary mirror. To assure proper function after deployment, the surface shape of this convex, hyperbolic mirror, approximately 80 cm in diameter, must be measured at cryogenic temperatures inside a large chamber. The size of the mirror, temperature, and vibration in the extremely noisy environment combined to make this measurement virtually impossible with any conventional interferometer.

To solve this difficult problem, a novel measurement method was incorporated by Ball Aerospace, relying on the capabilities of the FizCam 2000. In this method (Figure 6), a large reference optic is placed in front of the mirror, inside the vacuum chamber. Dynamic interferometry obviated the need to translate the reference, to couple the interferometer to the sample, or to employ vibration isolation, making it possible to place the FizCam outside the test chamber, several meters from the test and reference optics. This configuration also enabled the test and reference surfaces to be placed less than 1 cm apart, allowing the reference optics to be as small as possible. All of the intermediate optics required to expand the beam are common to both the test and reference beam paths, and therefore they do not contribute significant error to the measurement. The FizCam 2000 was the only system capable of cost-effectively completing this mission-critical measurement for JWST.

JWST Secondary Mirror Measurement

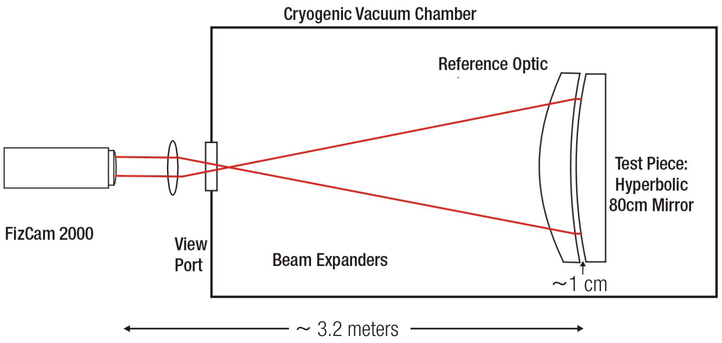

Figure 6. The 80 cm secondary mirror for the James Webb Space Telescope could only be measured under cryogenic conditions by using the FizCam 2000.

Conclusion

Dynamic interferometry has enabled complex measurements in difficult environments, from cryogenic test chambers to noisy shop floors. The FizCam 2000 dynamic Fizeau interferometer expands the capabilities of dynamic interferometry even further, providing the first cost-effective solution for accurate measurement of plane parallel optics, remote cavities and large convex mirrors.