An on-axis, vibration-immune Fizeau interferometer enables accurate measurement of fast spheres.

Measuring High NA Optical Systems without Retrace Error

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Introduction

Dynamic Interferometry® (spatial phase measurement) provides a near-instantaneous method for measuring surface shape and wavefront quality, even in the presence of vibration and air turbulence. This innovative technology is incorporated into 4D Technology's laser interferometers, which have enabled measurements in difficult environments and over long test paths.

Dynamic interferometry is available on several widely used interferometer configurations. For measurement of flat and focal optics, a Fizeau interferometer configuration (**Figure 1**) offers several advantages:

1. The Fizeau configuration requires only one high quality optical surface, so it has inherently fewer sources of variability.
2. In the Fizeau, the test and reference beams follow the same path through the interferometer ("on-axis, common path" design). Any errors in the internal optics cancel out, providing aberration-free measurement.
3. The on-axis, common path design also enables expansion of the beam to a much larger size, enabling measurement of concave and convex optics.

Off-axis = aberrations propagate

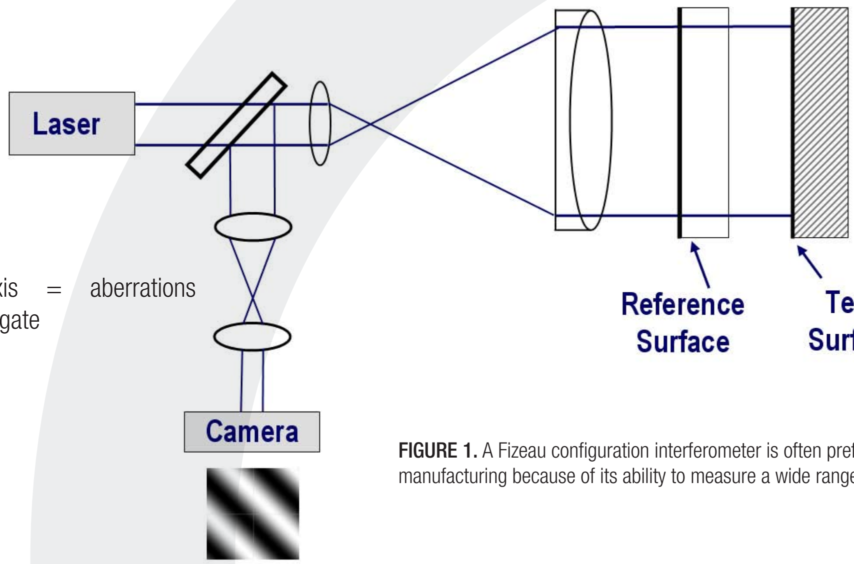

FIGURE 1. A Fizeau configuration interferometer is often preferred for optics manufacturing because of its ability to measure a wide range of optics.

Creating a Fizeau interferometer that is capable of dynamic measurement, however, has proved a significant challenge. The difficulty lies in maintaining the on-axis design while coding the source beam into two orthogonally polarized beams from the reference and test surfaces.

Tilted Beam Fizeau

One way to accomplish this separation is by applying fixed or variable tilt to one of the beams. Tilt can be used either to introduce a spatial carrier or to recombine the orthogonally polarized beams (**Figure 2**). It is important to note that when you "null" the test optic in such a system there are actually 30-250 fringes of nominal tilt between the test and reference beams. Any wavefront errors with higher spatial frequency than the frequency of the tilt fringes will be filtered from the data; therefore, even higher tilt is required to measure steeper local slopes.

Adding tilt, however, negates the on-axis, common path nature of the Fizeau configuration. Aberrations in the optical train now no longer cancel out. Introducing tilt into a high numerical aperture component, such as a transmission sphere, results in transmitted wavefront aberration. When an aberrated wavefront is launched into an optical system the return is not simply the original aberration plus the system aberration; instead, it is a complex wavefront that can only be understood through a full system ray-trace[1].

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Retrace error and shear between the test and reference beams result, both significantly reducing measurement accuracy. The effects are particularly pronounced when measuring high NA optical elements. To obtain the increased spatial resolution necessary to measure larger local slopes, even greater tilt must be introduced, generating greater retrace error.

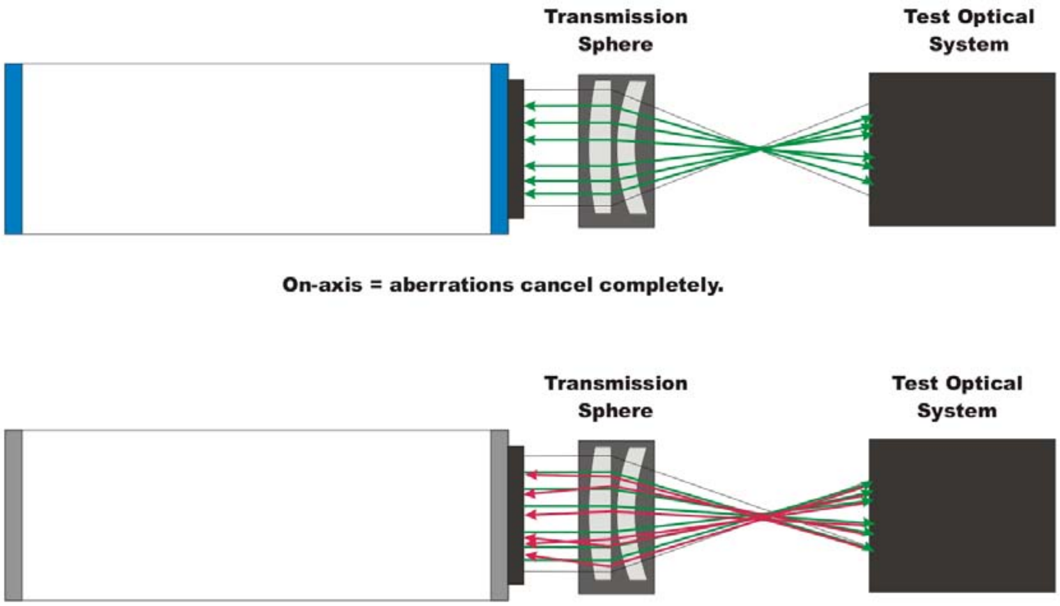

FIGURE 2. In an on-axis interferometer (above) aberrations in the optics cancel completely. If tilt is introduced (below), the reference and test beams are no longer common path. Aberrations propagate through the system that cannot be accurately calibrated out.

The removal of high spatial frequencies also results in ringing errors near the edge of the pupil. Ringing errors also occur in segmented apertures, such as multiple mirror systems, prisms, corner cubes, etc. In one study of a primary mirror partially obscured by the "spider" support structure for its secondary mirror, ringing errors in excess of $\lambda/3$ were recorded.

On-Axis Fizeau

In 2005 4D Technology introduced the first commercially available on-axis Fizeau interferometer. This system employed a short coherence source which enabled accurate measurement of thin, transparent optics and remote cavities. An internal "path matching" system was used to selectively interfere the on-axis reference and test beams such that they were orthogonally polarized. The system is effective for maximum external cavity distances up to approximately 2 meters.

4D Technology's follow-on interferometer, the FizCam 3000, is the first on-axis, dynamic Fizeau system with a long coherence source, enabling accurate measurement of focal and non-focal optics over short and long path lengths. The system employs a new technology called "Synchronous Frequency Shifting" (**Figure 3**). In this technique the beam is first divided into two polarizations (1). The reference surface and a second, internal mirror are rapidly translated in unison, parallel to the optical axis (2). The two beams are recombined and launched into the Fizeau cavity (3). There are now essentially four beams reflected from the Fizeau cavity: the s polarization with and without a frequency shift, and the p polarization with and without a shift. The net effect of the synchronized motion is that the fringes from all but one of the beam combinations are constantly moving, washing out to zero contrast (4). Only the *s* polarized beam from the test surface and the *p* polarized beam from the reference surface remain at high contrast and generate the interferogram (5).

With both beams on-axis, the common path advantages of the Fizeau configuration are maintained. Additionally, the use of a long coherence source eliminates the need to path match the test and reference arms of the interferometer.

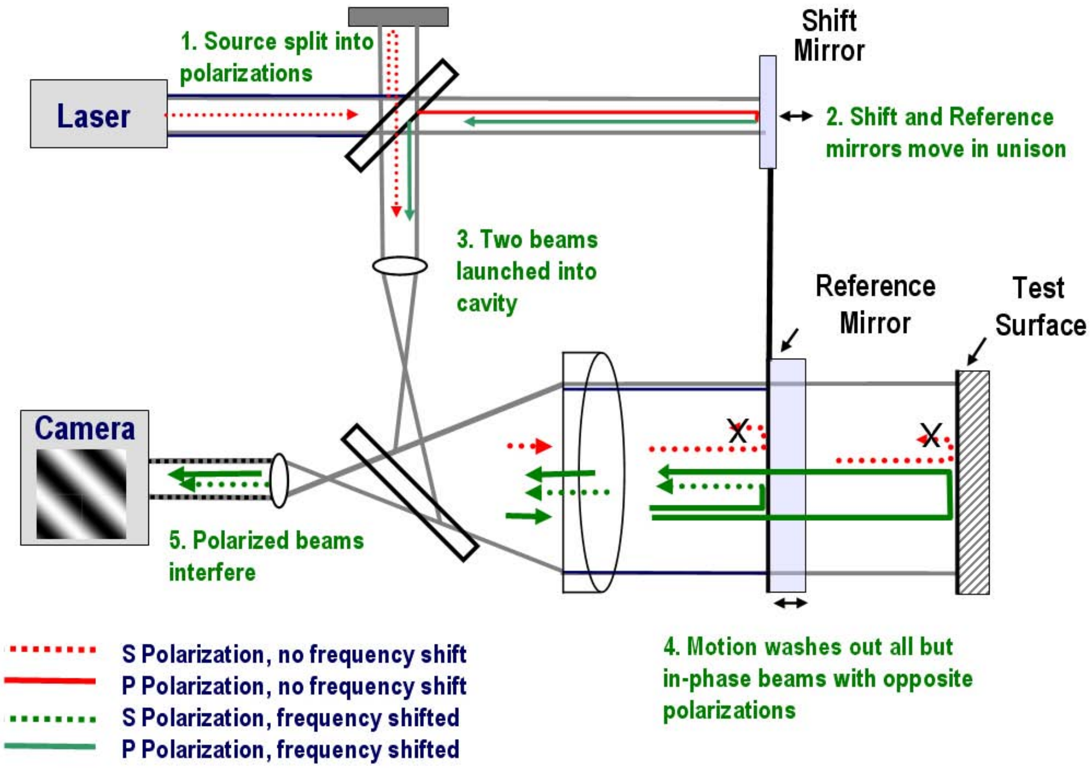

FIGURE 3. Using "Synchronous Frequency Shifting," only in-phased beams (green) of opposite polarization (solid and dotted) remain at high contrast and generate fringes.

Accurate Measurement of Spheres

One of the major benefits of the on-axis Fizeau is its ability to accurately measure spherical elements.

In competing techniques, added tilt induces significant retrace error, particularly when measuring spherical elements using high NA reference spheres. **Figure 4** shows that as tilt is increased to provide the spatial resolution necessary to measure the sphere, the retrace error also rises dramatically.

To demonstrate, the convex surface of an f 1.5, $\lambda/10$ reference sphere was measured with induced tilt varying from 0 waves (on-axis) to 300 waves. When approximately 250 waves of tilt were applied to the test beam, as is common with Spatial Carrier systems, peak-to-valley retrace error in excess of 1.5 waves was generated. In systems with variable tilt a smaller tilt angle can minimize retrace error but only at the sacrifice of spatial resolution.

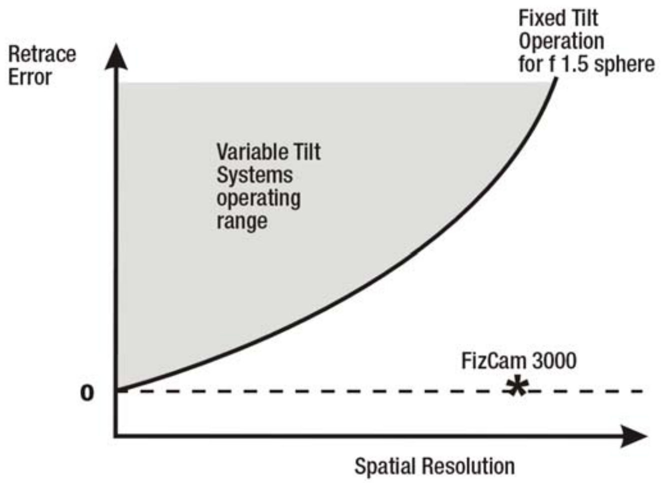

FIGURE 4. Retrace error vs. Resolution for an f1.5 sphere. As tilt is increased to provide better spatial resolution, retrace error also increases, limiting performance for tilted beam systems. The FizCam 3000 achieves high spatial resolution and minimal retrace error.

The Limitations of Calibration

Designers of tilted beam systems rely on software-based calibration to reduce these errors. The calibration procedure consists of measuring the aberrations of the optical system using an extremely high quality test surface. This reference measurement is then removed from subsequent test data, presumably leaving only the contribution of the test optic in the actual data.

Calibration can indeed remove small, static system aberrations. Yet even when measuring a very good return sphere one can calibrate out the off-axis error only for measuring high quality spheres of similar radius. This is a very narrow subset of useful applications.

When measuring a fast sphere in a tilted beam system the inherent error can be more than 15 times greater than that of the test surface's peak-to-valley height. In this case, slight changes in the system or the environment have the potential to render the calibration incorrect and ineffective. Moreover, retrace errors vary as a function of cavity distance, also making it extremely difficult to determine and maintain accurate calibration.

Therefore, it is essential that the test beam be nearly diffraction limited in order to return a true measure of the system aberration. This is only truly possible using an on-axis, common path design.

Conclusion

The FizCam 3000 is the only commercially-available on-axis, dynamic Fizeau interferometer. It combines the resolution and flexibility of a Fizeau laser interferometer with the ability to measure despite vibration and turbulence, for real-world quality assurance of advanced research optics.

References

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