Advances in Interferometric Metrology

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ABSTRACT

Modern electronics, computers, and software have made interferometry an extremely powerful tool in many fields including the testing of optical components and optical systems. This paper will discuss some of the recent advances in reducing the sensitivity of phase-shifting interferometers to vibration.

Keywords: interferometry, metrology, optical testing, interference, optical measurements

1. INTRODUCTION

In the testing of optical components and optical systems there are many requirements on the precision and accuracy, measurement time, ease of use, dynamic range, and environmental conditions. Interferometry, and in particular phase-shifting interferometry, has the precision and potential accuracy required for most optical tests. Ease of use is generally acceptable, but often the requirements for the environmental conditions are more severe than desired and sometimes the desired measurement cannot be performed because of vibration. It is common for the overall test measurement accuracy to be determined by the vibration present. This paper will discuss some recent advances in reducing effects of vibration by using phase-shifting common-path interferometers such as the scatterplate interferometer and single shot phase-shifting interferometers.

2. COMMON PATH SCATTERPLATE INTERFEROMETER

Common-path interferometers have reduced sensitivity to vibration because at least part of the vibration is common to both the test and the reference beams. One common-path interferometer in which the piston component of the vibration is common to both the test and the reference beam is the scatterplate interferometer invented by Jim Burch in 1953[1-2]. The scatterplate interferometer is a common path interferometer that automatically matches interferometer paths so a zero order fringe is obtained whose position is independent of wavelength. The configuration of a scatterplate interferometer for testing spherical mirrors is shown in Figure 1. A magnified image of the scatterplate is shown in the upper left corner of the figure. A small circular aperture is illuminated with a laser or broadband source producing a source of limited extent for the interferometer. A focusing lens is used to image the source onto the test mirror by way of a beam splitter that removes the source from the path of the return beam and a scatterplate. The scatterplate is placed at the center of curvature of the test mirror. Part of the light incident on the scatterplate scatters illuminating the entire mirror surface and part of it passes directly through imaging to a point on the test mirror. After reflecting off the test surface the light again propagates through the scatterplate scattering a portion of the beam. A focusing lens is used to image the interference fringes onto a screen or detector.

To understand what produces the interference fringes we need to look more closely at the effect of the scatterplate. Each time the light encounters the scatterplate some of it is scattered and a portion passes directly through the plate. Since the scatterplate is traversed twice there are four permutations of the beam that arrive in the image plane: 1) Scattered-Scattered, 2) Scattered-Direct, 3) Direct-Scattered, and 4) Direct-Direct. An examination of each of these combinations will uncover their role in producing fringes. The direct-direct beam passes directly through the scatterplate both times it is encountered forming an image of the source called the “hot spot” in the image plane. Since the “hot spot” is never scattered, it does not contribute to the production of interference fringes. Similarly, the scattered-scattered beam does not play a role in the formation of interference fringes. The light is scattered both times it passes through the scatterplate

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producing background irradiance in the image plane. The direct-scattered beam is the reference beam of the interferometer. The light passes directly through the scatterplate on the first pass and forms an image of the source on the test surface. If the image of the source is small enough the phase variations introduced into the beam on reflection are negligible. On the return leg the light is scattered. The scattered-direct beam serves as the test beam of the interferometer. The light is scattered on its initial pass through the scatterplate illuminating the entire test mirror. Any departures from a sphere will introduce phase variations in the beam. The light then passes directly through the scatterplate producing fringes when it interferes with the reference beam.

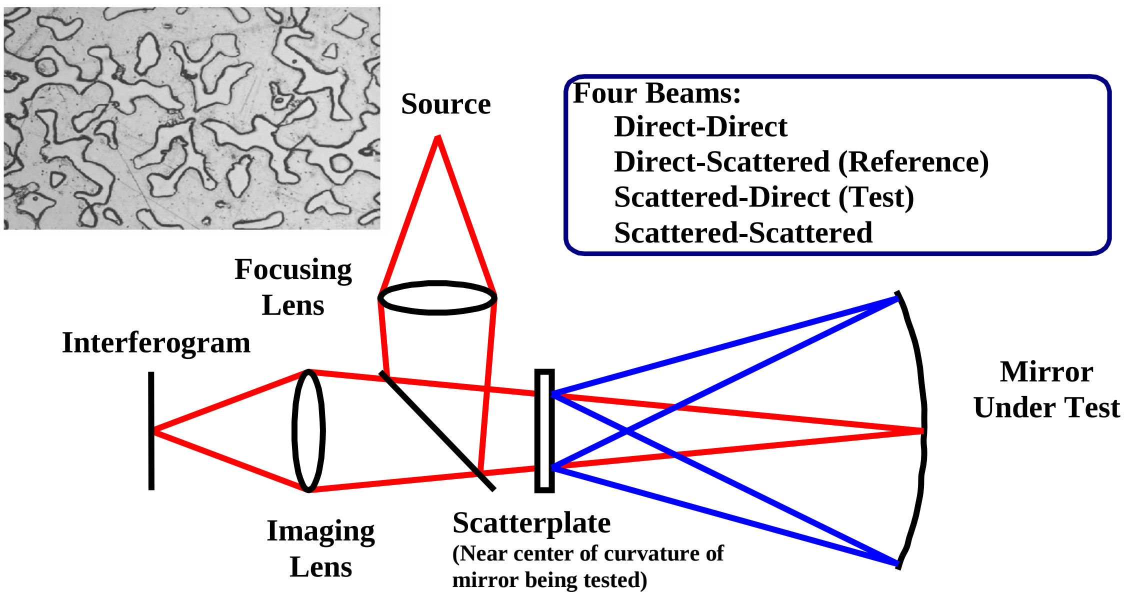

Figure 1. Scatterplate Interferometer for Testing Concave Mirrors.

It seems unlikely that two beams of light that have been scattered at different positions in the interferometer could possibly produce interference fringes. In general, the process described above would not produce meaningful interference fringes, however if the scatterplate has inversion symmetry[2] interference fringes showing the quality of the mirror under test are obtained. Inversion symmetry means that each scatter point has an exact twin located directly opposite the center point of the scatterplate as shown in Figure 1. The reason inversion symmetry works is revealed by examining individual scatter points and their effect on the reference and test beams. Keep in mind that examining individual points is not the complete story. Summing the wavefronts from all of the scatter points forms the contour fringes. Figure 2a summarizes the effect of inversion symmetry for a perfectly aligned system. When the incident light interacts with the scatterplate, the light scattered at scatter point S(x,y) acts like a point source. Since the scatterplate is located at the center of curvature of the test mirror, point S(x,y) is imaged back into the plane of the scatterplate at the conjugate point S'(x,y). The reference beam passes directly through the scatterplate reflects off the test mirror and scatters at point S(-x,-y). With inversion symmetry and proper alignment point S(x,y) and S(-x,-y) are scattered in exactly the same manner and the test and reference beams both appear as point sources located at point S(-x,-y). As a result, the phase change due to scattering is the same for both beams.

The above discussion of inversion symmetry was for a system with perfect alignment. The effect of misalignment of the scatterplate will now be discussed. Lateral movement of the scatterplate produces tilt in the contour fringes. Figure 2b demonstrates the consequence of not aligning the center point of the scatterplate with the axis of the interferometer. The image of S(x,y), although still in the plane of the scatterplate, no longer coincides with the symmetric point S(-x,-y). The result is tilt in the contour fringes produced by the interference of two laterally shifted point sources. Similarly, longitudinal misalignment of the scatterplate adds defocus to the contour fringe pattern. Figure 2c shows the effect of not placing the scatterplate at the center of curvature of the test mirror. The image of point S(x,y) is still at the same lateral position as the symmetric point S(-x,-y), however it no longer lies in the plane of the scatterplate. The interference of the two longitudinally shifted point sources produces defocus in the contour fringes. Adjusting the scatterplate position adds an important flexibility for minimizing the number of contour fringes across the image plane.

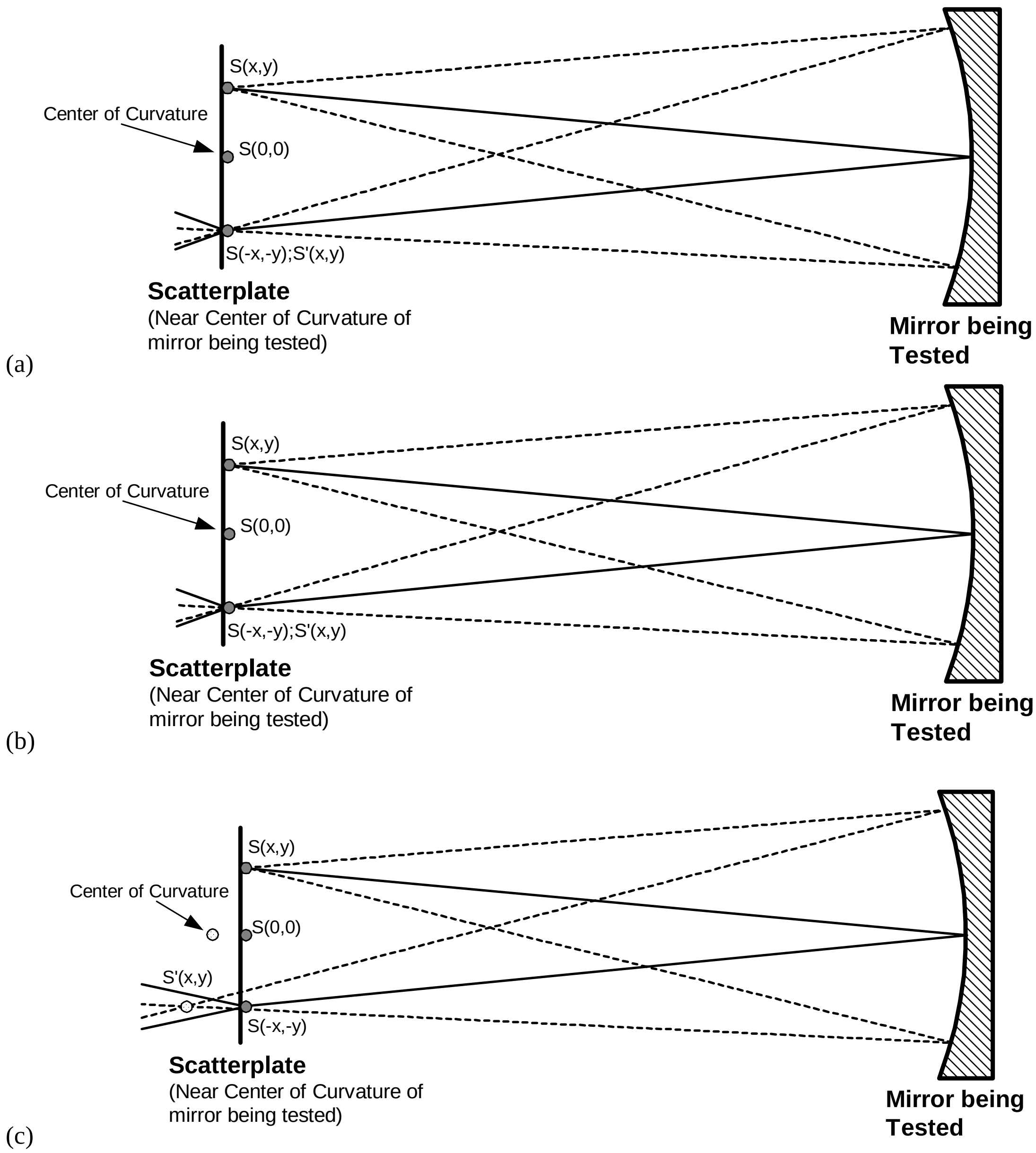

Figure 2. Point-To-Point Analysis of Inversion Symmetry: (a) Perfect Alignment, (b) Lateral misalignment of Scatterplate, (c) Longitudinal Misalignment of Scatterplate.

A typical interferogram is shown in Figure 3. The source in this case consisted of several laser lines. It should be noted that the zero order fringe passes through the hot spot. For this fringe the two interferometer paths are matched.

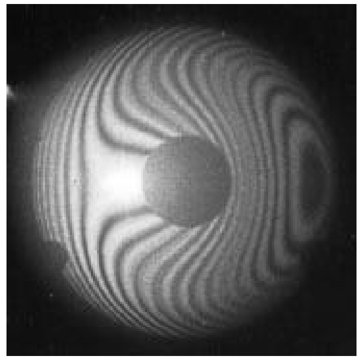

Figure 3. Typical scatterplate interferogram.

The scatterplate interferometer can be modified as shown in Figure 4 so it is insensitive to both tip-tilt vibration and piston vibration.[3] In this case the scatterplate is imaged onto a mirror and then reimaged onto itself and it does not need to have inversion symmetry and in fact any partial scattering diffuser will work as the scatterplate. The disadvantage of this version of the scatterplate is that while it is insensitive to vibration it does not measure the odd aberrations of the mirror under test. For this reason, it is seldom used in a test setup.

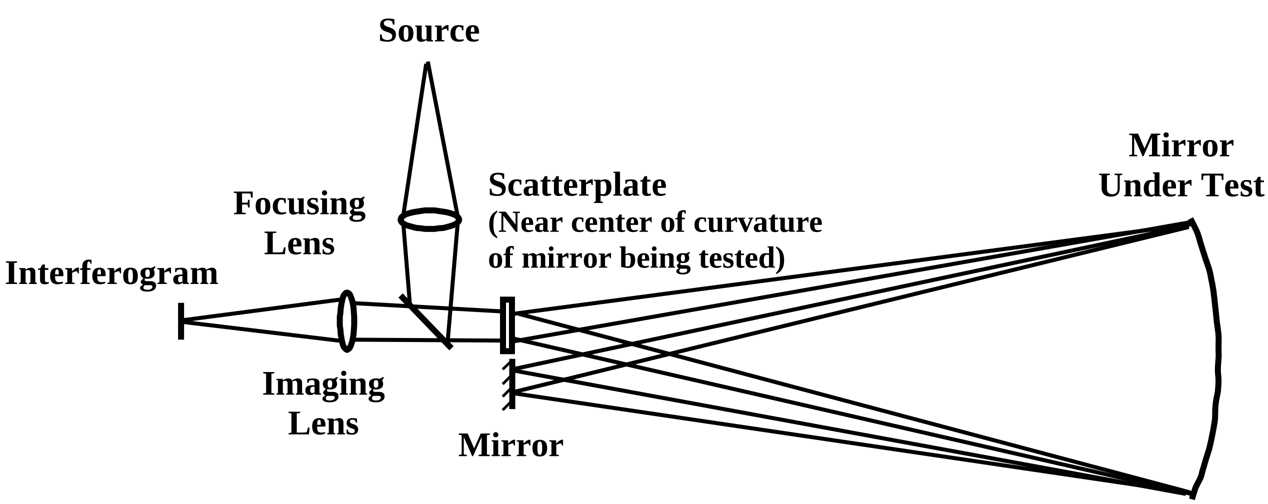

Figure 4. Scatterplate Interferometer insensitive to tip-tilt and piston vibration.

3. PHASE-SHIFTING COMMON PATH SCATTERPLATE INTERFEROMETER

Phase-shifting interferometry is especially sensitive to vibration because several frames of data are taken sequentially in time with a precise phase shift between consecutive frames. Typically the frames are taken at a rate of 30 frames/sec with a phase shift of 90 degrees between consecutive frames. Vibration causes the phase difference between consecutive frames to be incorrect and hence incorrect measurements are obtained. Often great effort is used to reduce the vibration present so good measurements can be obtained, however in some instances such as the testing of large telescope mirrors getting rid of the vibration can be an extremely expensive. As discussed above, one way of reducing the effects of vibration is to use a common-path interferometer where essentially the same vibration is present in the test and reference beams so the vibration effects nearly cancel.

While common-path interferometers are one possible solution to the environmental limitations, since the test and reference beams traverse the same optical path it is difficult to separate the test and reference beams for phase shifting.

The scatterplate interferometer has been successfully phase shifted by J. Huang et. al.[4] and D. Su et. al.[5]. Both methods exploit polarization to separate the test and reference beams by placing an auxiliary optic near the test mirror. Huang et. al. placed a small quarter-wave plate near the test surface which rotated only the incident linear polarization of the reference beam by 90º. With orthogonal polarizations in the test and reference beams the interferometer is phase shifted using an electro-optic light modulator. Su et. al. playing on the same theme, placed a large polarizer with a small hole in the center near the test surface. In combination with additional polarization manipulating optics, the polarizer rotates the polarization of the test beam 90º.

Another approach recently introduced that works extremely well is to use a birefringent scatterplate[6]. With a phase-shifting scatterplate interferometer, the goal is to control when the test and reference beams are scattered. Here the birefringent scatterplate shown in Figure 5 provides the desired control. The appropriate aperiodic pattern with inversion symmetry is etched into a calcite retarder using a chemical etching process. An index matching oil chosen to match the ordinary index of the crystal is then pressed between the calcite and a glass slide. The end result is that for light polarized along the ordinary axis of the crystal, the index of the oil and the index of the crystal appear the same and the light passes directly through the scatterplate, whereas light polarized along the extraordinary axis of the crystal sees an index difference and is scattered by the rough surface. This is the property that controls whether the test or the reference beam is scattered.

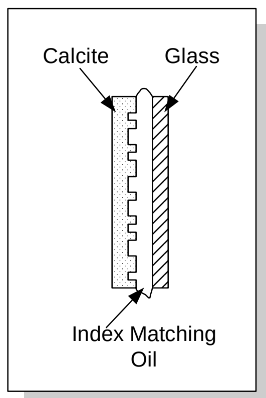

Fig. 5. Birefringent scatterplate.

A schematic diagram of the phase shifting scatterplate interferometer is shown in Figure 6. If the polarization elements such as the wave plates and polarizers are removed, it is a conventional scatterplate interferometer. The polarizer passes linearly polarized light oriented at 45º with respect to the optic axis of the calcite scatterplate, providing equal amplitudes for the component of the beam polarized along the optic axis and the component polarized orthogonal to the optic axis. The component parallel to the optic axis will see the extraordinary index of the crystal and the perpendicular component will see the ordinary index. A liquid crystal retarder produces a variable phase shift between the two orthogonal components of polarization. The scatterplate is located at the center of curvature of the test mirror and scatters only the component of the beam that is polarized parallel to the optic axis of the crystal. The perpendicular component passes through the scatterplate and forms an image of the source on the test mirror. Both the scattered and direct beams pass through a quarter-wave plate twice producing a 90º rotation in the direction of polarization of each. As a result, on the second pass through the scatterplate the beams change roles and the one that traveled directly through on the first pass is now scattered and the one that was scattered now passes directly through. The outcome is a scattered-direct and direct-scattered beam with orthogonal polarization. The end result is that the interference fringes can be phase shifted by applying a voltage to the liquid crystal retarder.

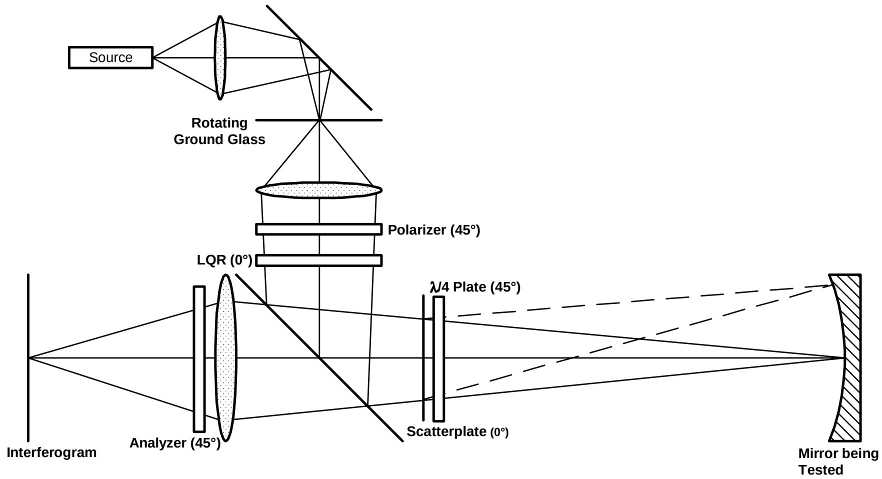

Fig. 6. Phase-shifting scatterplate interferometer.

4. PHASE-SHIFTING SINGLE-SHOT INTERFEROMETER

Another technique for reducing the effects of vibration in phase-shifting interferometers is to take all the phase shifting frames at once. Figure 7 shows one technique for obtaining 4 phase-shifted interferograms simultaneously. The light coming from the laser is linearly polarized at 45-degrees with respect to the x and y axes. An eighth wave plate is put in the reference beam such that after the reference beam is transmitted through the eighth wave plate two times the x and y components of the reference beams are out of phase 90 degrees. A polarization beamsplitter, PBS 1, in the output reflects the y component and transmits the x component producing two interferograms that are out of phase by 90 degrees. If beamsplitter #1 in the interferometer is a dielectric beamsplitter the interferograms in the beam going back to toward the laser are 180 degrees out of phase with respect to the normal output. Beamsplitter #2 picks off a portion of these beams and a second polarization beamsplitter, PBS 2, gives two outputs that have 180 and 270 degrees phase shift.

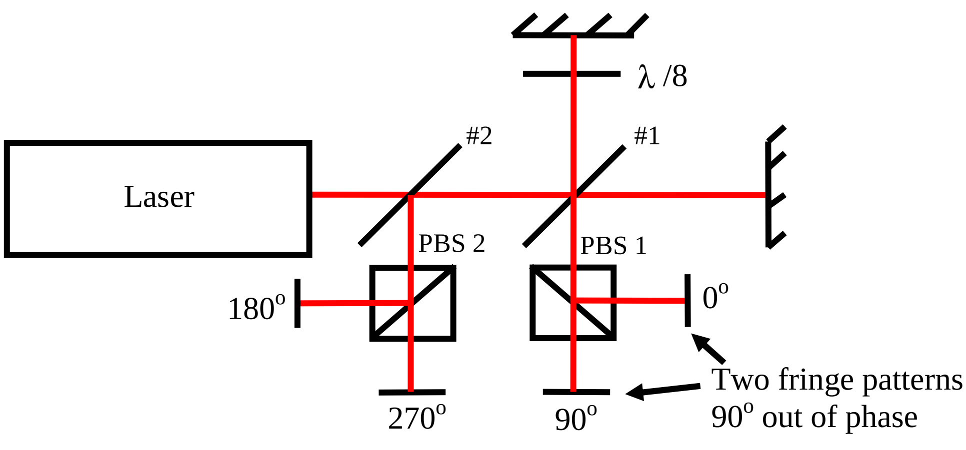

Figure 7. Simultaneous phase-shifting interferometer.

While single-shot phase shifting interferometers of this type have been available for some time they normally use four-separate CCD cameras and as a result both the calibration and the alignment of the four cameras are very critical and accuracy can suffer[7].

A better approach is to have all four phase-shifted frames fall on a single CCD camera[8] as shown in Fig. 8. In this arrangement, a Twyman-Green interferometer is used where the reference and test beams have orthogonal polarization. After the two beams are combined they pass through a holographic element that splits the beam into four separate beams resulting in four interferograms. These four beams pass through a birefringent mask that is placed just in front of a CCD camera. The four segments of the birefringent mask introduce phase shifts between the test and reference beams of 0, 90, 180, and 270 degrees. A polarizer with its transmission axis at 45 degrees to the direction of the polarization of the test and reference beams is placed after the phase masks just before the CCD array. Thus, all four phase shifted interferograms are detected in a single shot on a single detector array.

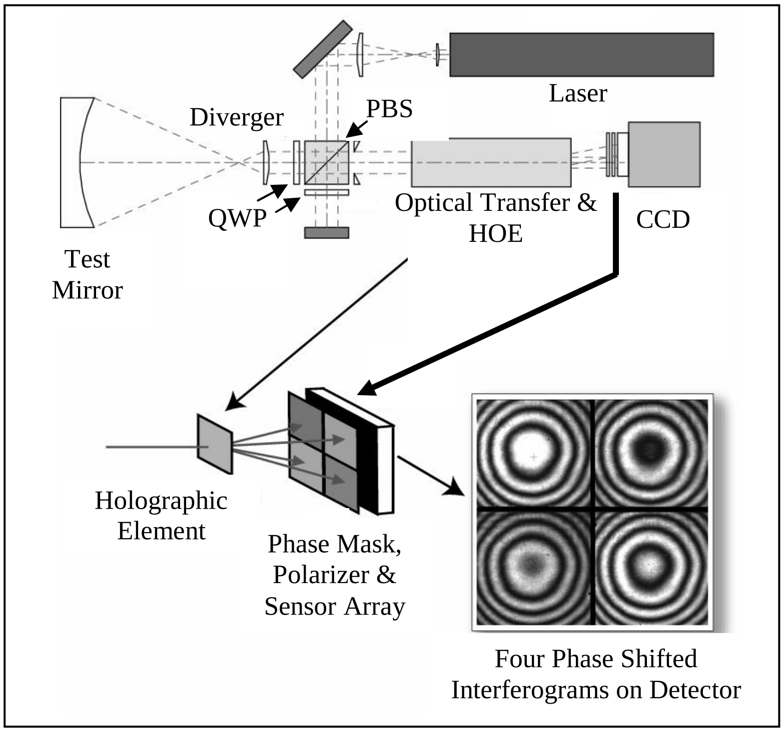

Fig. 8. Single shot interferometer (PhaseCam) showing the beam divider and phase shifting mask.

Figure 9 shows the single shot PhaseCam interferometer testing a 0.5 meter diameter, 20 meter ROC mirror without any vibration isolation. Measurements can be averaged to reduce the effects of air turbulence to give nm or better accuracy without vibration isolation.

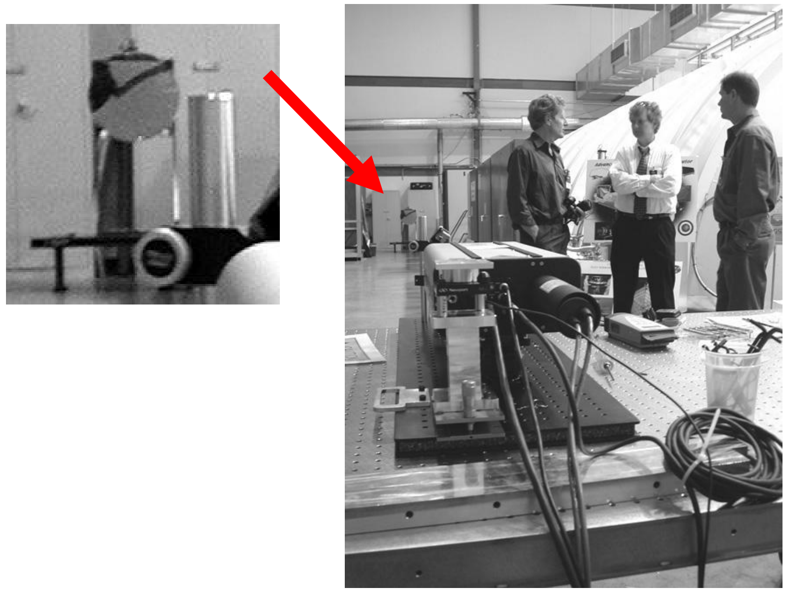

Figure 9. Use of PhaseCam to test a 0.5 meter diameter, 20 meter ROC mirror without any vibration isolation.

By making short exposures the vibration is frozen and vibrational modes can be measured. Figure 10 shows an example of measuring vibrational modes of a disk as a function of frequency. Movies can be made showing the vibration.

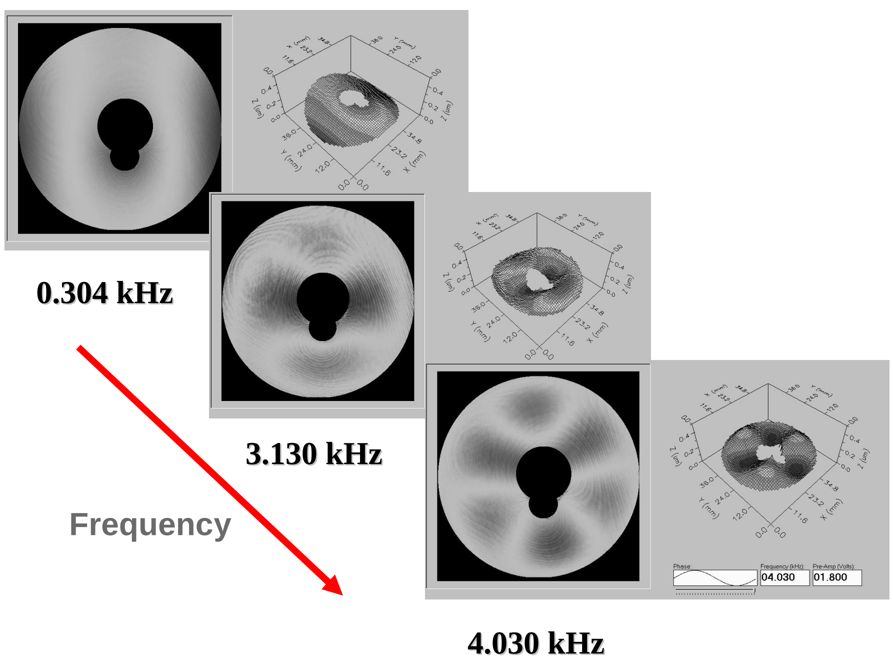

Figure 10. Vibrational modes of a disk.

5. CONCLUSIONS

A phase shifting common path interferometer such as a phase-shifting scatterplate interferometer or a single shot phase shifting interferometer can go a long way in reducing the effects of what is often the largest source of error in phase shifting interferometry, namely vibration.

6. REFERENCES

1. J. M. Burch, "Scatter Fringes of Equal Thickness," *Nature* 171, p. 889, 1953.
2. J. M. Burch, "Interferometry in Scattered Light," *Optical Instruments and Technique*s, J.H. Dickson, ED.,Oriel Press, England, pp. 220-229, 1970.
3. A. H. Shoemaker and M. V. R. K. Murty, "Some Further Aspects of Scatter-Fringe Interferometry," *Appl. Opt*. **5**, pp. 603-607, 1966.
4. Huang, Junejei et. al., "Fringe Scanning Scatter Plate Interferometer using a Polarized Light", *Opt. Com*m., **68**, pp. 235-238, 1988.
5. Su, Der-Chin and Lih Horng Shyu, "Phase-shifting Scatter Plate Interferometer Using a Polarization Technique," *J. Mod. Opt*., **38**, pp. 951-959, 1991.
6. Michael B. North-Morris, Jay VanDelden, and James C. Wyant, "Phase-shifting birefringent scatterplate interferometer," *Appl. Opt*. **41**, pp. 668-677, 2002.
7. Chris L. Koliopoulos, "Simultaneous phase-shift interferometer," in, Advanced Optical Manufacturing and Testing II, Victor J. Doherty; Ed., Proc. SPIE Vol. 1531, p. 119-127 (1992)
8. U. S. Patent 6,304,330, James E. Millerd and Neal J. Brock, (2001).

7. ACKNOWLEDGEMENTS

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