Vibration Insensitive Interferometric Optical Testing

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Abstract: The measurement accuracy of an interferometric optical test is generally limited by the environment. This paper discusses two single-shot interferometric techniques for reducing the sensitivity of an optical test to vibration; simultaneous phase-shifting interferometry and spatial carrier interferometry.

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1. Introduction

In the testing of optical components and optical systems there are many requirements on the precision and accuracy. Interferometry, and in particular phase-shifting interferometry, has the precision and potential accuracy required for most optical tests. The largest limitation of phase-shifting interferometry is the sensitivity to the environment, both vibration and air turbulence. In many situations the measurement accuracy is limited by the environment and sometimes the environment is sufficiently bad that the measurement cannot be performed. This talk will discuss advances in reducing effects of vibration by using single-shot interferometric techniques; simultaneous phase-shifting interferometry and spatial carrier interferometry. If the interferometer is insensitive to vibration many measurements can be averaged to reduce the effects of air turbulence.

2. Simultaneous phase-shifting interferometer

An interferometer using temporal phase-shifting is very sensitive to vibration because the various phase shifted frames of interferometric data are taken at different times and vibration causes the phase shifts between the data frames to be different from what is desired. Vibration effects can be reduced by taking all the phase shifted frames simultaneously. There are several techniques for simultaneously obtaining 3 or more phase-shifted interferograms. While so called simultaneous phase shifting interferometers 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 [1]. A superior approach is to have all four phase-shifted frames fall on a single CCD camera as shown in Figure 1 [2, 3].

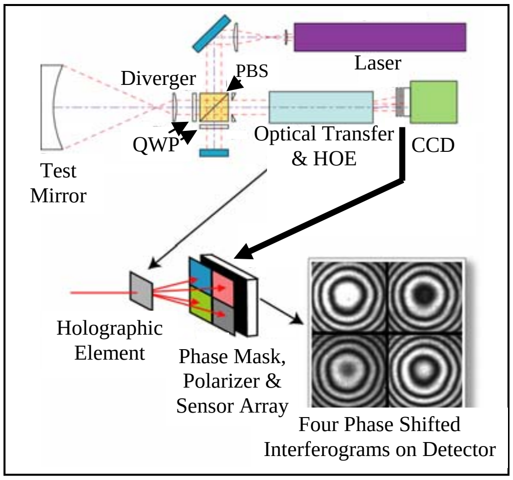
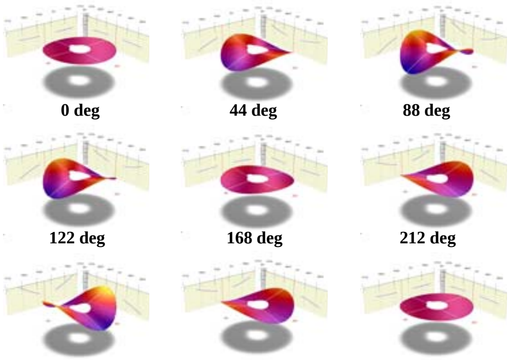


Fig. 1. Simultaneous phase-shifting interferometer (PhaseCam).

In this arrangement an interferometer is used where a polarization beamsplitter causes the reference and test beams to have orthogonal polarization. Quarter-wave plates are placed in the reference and test beams so the beam transmitted the first time through the beamsplitter is reflected the second time, and vice versa. After the two orthogonally polarized 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 the 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 simultaneously on a single detector array.

By making short exposures the vibration, as well as the air turbulence, is frozen. The effects of air turbulence can be reduced by taking many sets of data, where the time between the different data sets is long compared to the time it takes for the turbulence to change, and then averaging the data.

Not only can the effects of vibration be eliminated, but by making short exposures to freeze the vibration the vibrational modes can be measured. Figure 2 shows an example of measuring vibration of a disk driven at a frequency of 408 Hz. Movies can be made showing the vibration. Likewise, flow fields can be measured.



0 deg **44 deg** **88 deg**

122 deg **168 deg** **212 deg**

266 deg **310 deg** **360 deg**

Fig. 2. Measurement of vibration of a disk (408 Hz.)

3. Spatial carrier interferometry

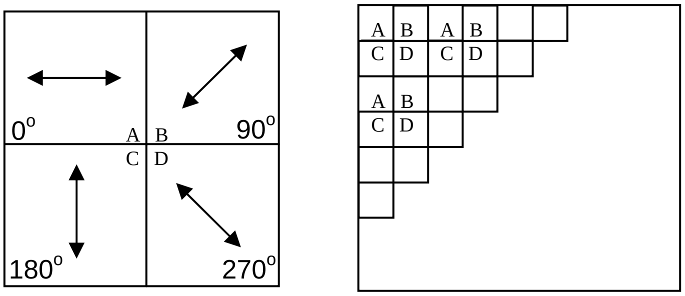
In spatial carrier interferometry a single interferogram is taken that has a lot of tilt fringes [4]. The exposure time for the interferogram is short enough that the vibration is frozen. Two approaches for analyzing the spatial carrier interferogram will be discussed. To understand the first approach it is convenient to think of the interferogram as a hologram.

If in the making of a hologram enough tilt is introduced between the object and reference beam then in the reconstruction process the reconstructed object beam will separate from the other reconstruction orders. Equivalently, if the interferogram intensity distribution is Fourier transformed and filtered to select out the first order and this first order is Fourier transformed again, the wavefront is obtained. Just like for a hologram, a sufficient number of tilt fringes must be present so the first Fourier transform can be adequately filtered. This technique works reasonably well, but the filtering process smoothes the wavefront and the accuracy of the wavefront near the edge of the pupil is limited.

A second analysis approach that works with a single interferogram having many tilt fringes present assumes that across a relatively small window the wavefront may be considered flat [5]. Then across the small window the phase varies linearly and the phase difference between adjacent pixels is constant and the normal phase-shifting algorithms can be used. For example, let’s assume the tilt between the two interfering beams is selected so there are four detector elements between fringes. In this case the phase of the tilted reference wave changes 90 degrees between adjacent detector elements (360 degrees between fringes). Phase-shifting algorithms can then be used to calculate the phase using the intensities measured by four adjacent detectors. This technique would work well if the test wavefront has no aberrations because then the fringes would be equally spaced. If aberrations are present the fringe spacing changes and the detector spacing is no longer exactly one-quarter the fringe spacing. However, as the aberrations become larger the accuracy to which the phase distribution must be measured is decreased, so this measurement technique still often works sufficiently well. Many different algorithms have been derived to reduce the requirements on the flatness of the wavefront across the sampling window [6].

A critical item is the method for obtaining the carrier fringes. While the carrier fringes can be obtained by tilting the reference mirror this is generally not acceptable because retrace errors introduced by having a large angle between the two interfering beams in the interferometer cause additional aberrations. A better approach that does not require the test and reference beam to have a large angle between them in the interferometer is to have the reference and test beams have orthogonal polarization and then a phase filter is placed directly in front of the detector to introduce a tilt angle between the two beams. A common phase filter is a Wollaston prism followed by a polarizer which will introduce the required tilt between the two interfering beams to obtain the carrier fringes.

A phase filter that works better because the phase shift between the two interfering beams is nearly independent of wavelength is a quarter waveplate followed by linear polarizers at different angles. The quarter waveplate is oriented to convert the test beam into right-handed circular polarization and the reference beam into left-handed circular polarization. If these circularly polarized beams are transmitted through a linear polarizer a phase shift between the two interfering beams proportional to twice the rotation angle of the polarizer results. Thus, if a phase mask is made of an array of 4 linear polarizer elements having their transmission axes at 0, 45, 90, and 135 degrees as shown in Figure 3, where a polarizer element is placed over each detector element, the mask will produce an array of four 0, 90, 180, and 270 degrees phase shifted interferograms. While an achromatic quarter waveplate could be used to extend the spectral range the phase mask would work for, it turns out that the phase shift produced by the rotated polarizers does not depend greatly upon the quarter-wave plate being a true quarter-waveplate [7].



(a) (b)

Fig. 3 Phase filter. (a) 4 polarizer elements giving 0, 90, 180, and 270 degree phase shifts.
(b) Phase filter made up of array of 4 polarizer elements.

4. Conclusions

A single shot interferometer, whether it is a simultaneous phase shifting interferometer or a spatial carrier 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. Errors due to air turbulence can be reduced by averaging many frames of data obtained using a single shot interferometer.

5. References

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6. Miscellaneous

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