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Defocus Measurement Using a Liquid Crystal Point Diffraction Interferometer

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Introduction

A liquid crystal phase-stepped point diffraction interferometer (LCPDI) has been developed to measure optical wavefronts[1]. A locally generated reference beam is generated by diffraction from a microsphere embedded in a thin liquid crystal layer. Phase shifting is achieved by applying a voltage across the birefringent liquid crystals to shift the phase of the object beam without affecting the reference beam. The intended application for this instrument is the measurement of phase objects, such as optical elements and slowly varying fluids.

In flow metrology, wavefronts are commonly measured both before and after a flow disturbance and the difference is determined. This paper presents data indicating that the LCPDI will be useful for measuring such phase objects. Two wavefronts differing only by the amount of defocus were chosen for measurement by the LCPDI. This phase object was chosen because the focus change can be easily verified by calculation.

The LCPDI currently has the unwanted side-effect of object beam intensity modulation along with phase modulation. Two techniques designed to compensate for this intensity variation are described in this paper. These techniques require the measurement of both the phase shifted interferograms and the object beam intensity distributions at each applied voltage.

Experimental Apparatus and Procedure

The liquid crystal point diffraction interferometer (LCPDI) consists of dyed parallel nematic liquid crystals sandwiched between two glass plates. A transparent microsphere placed between the glass plates near the center of the clear aperture displaces a small volume of liquid crystal. Coherent light is brought to a focus near the microsphere. The focused spot is larger than the microsphere so some of the beam travels through the liquid crystal forming the object beam. The rest is diffracted by the microsphere and forms the reference beam.

The glass plates have transparent electrodes deposited on their inner surfaces. Leads are soldered onto the electrodes so that an alternating current can be applied across the liquid crystal. The applied field reorients the liquid crystal molecules and changes the refractive index of the liquid crystal layer. The phase of the object beam can thus be altered without affecting the reference beam.

Dye is added to the liquid crystals in order to attenuate the object beam to roughly the same intensity as the reference beam. This improves the fringe contrast, but the dye molecules rotate with the liquid crystal molecules causing an unwanted intensity modulation when the phase is shifted.

A schematic of the optical system is shown in Fig. 1. A laser beam is brought to focus just before the liquid crystal filter (LCPDI POS1). The LCPDI is tilted to reduce the effects of multiple reflections. The phase shift between the object and reference beams is set to $j\pi/2$ radians (where $j = 0,1,2,3,4$) by applying a voltage sequence ranging from 1.04 to 1.55 VAC across the electrodes. The interferograms are formed on a ground glass screen (SCR) placed behind the LCPDI and are recorded with a CCD camera. In order to measure the intensity distribution of the object beam alone, the LCPDI plate was translated by 0.75 mm along the x1-axis so that the focused beam did not pass through any microspheres. The light incident on the screen was recorded for each applied voltage. The amount of defocus was then increased by moving the LCPDI along the optical axis by $\delta z = 0.34$ mm. Slight in-plane adjustments were made to center the new interference pattern on the CCD. Again, the interferograms were recorded, then the LCPDI plate was translated in order to record the object beam alone.

Data reduction

Standard algorithms for the extraction of wavefront phase can not be used for these interferogram sequences because the average intensity across each image varies from frame to frame. Two approaches were taken to compensate for this intensity variation. In order to evaluate the performance of these compensation techniques, the wavefronts were first computed from the raw interferograms using Hariharan's 5-frame algorithm[2]. This algorithm was chosen because of its robustness in the presence of phase stepping error.

Each frame of object beam intensity data was smoothed with a boxcar average over 25 pixels to decrease the speckle and multiple beam interference effects in the frames. A 2-D sixth-order polynomial was fitted to each smoothed intensity frame to form normalization frames I_j^{obj}, where again $j = 0,1,2,3,4$.

For the first compensation method, each interferogram I_j is divided by the appropriate normalization frame, then used in the 5-frame algorithm as follows:

$$\tan(\phi) = 2[\, I_3/I_3^{obj} - I_1/I_1^{obj}\,] \,/\, [\, I_0/I_0^{obj} + I_4/I_4^{obj} - 2I_2/I_2^{obj}\,] \qquad (1)$$

The second method uses the object beam intensity to explicitly solve for the wavefront phase. Assuming that the reference beam intensity remains constant from frame to frame, the wavefront phase ϕ can be calculated as follows:

$$\tan(\phi) = \{ [\Delta I_3 - \Delta I_1] / [\Delta I_0 + \Delta I_4 - 2\Delta I_2] \} * \{ [\mathrm{sqrt}(I_0^{obj}) + \mathrm{sqrt}(I_4^{obj}) + 2\mathrm{sqrt}(I_2^{obj})] / [\mathrm{sqrt}(I_3^{obj}) + \mathrm{sqrt}(I_1^{obj})] \} \qquad (2)$$

where $\Delta I_j = I_j - I_j^{obj}$.

The wavefronts for both positions of the LCPDI were computed using the standard 5-frame algorithm on the raw interferograms and the intensity compensation algorithms given by Eqns. 1 and 2. Also, 2-D polynomials were fitted to the wavefronts computed from the raw interferograms. The wavefront difference was obtained by subtracting the two wavefronts obtained by each of the four methods.

Theoretical analysis

The difference in the optical phase between the wavefronts at each LCPDI position can be calculated from:

$$\Delta\phi_{th}(r,\delta z) = \{ \mathrm{sqrt}(D^2 + r^2) - \mathrm{sqrt}[(D-\delta z)^2 + r^2] - \delta z \} 2\pi/\lambda \qquad (3)$$

where D is the distance from the LCPDI to the ground glass viewing screen, δz is the axial distance between the two positions of the LCPDI, and r is the radial distance from the center of the interferogram.

Results

Fig. 2 shows horizontal cross sections from the wavefront differences computed using each of the methods described above together with the corresponding cross section from the theoretical wavefront difference calculated from Eqn. 3. It can be seen that in each case the wavefront difference is accurately measured. The standard deviations from the theoretical wavefront for each of the computed wavefront differences are 5.1, 25.4, 14.1, and 14.9 for the wavefront differences computed from: polynomial fits to the wavefronts computed from the 5-frame algorithm, the 5-frame algorithm, Eqn. 1, and Eqn. 2, respectively. Equations 1 and 2 produce similar results and provide significant improvement over the standard 5-frame algorithm. The amount of periodic error is reduced by these intensity compensation algorithms but not eliminated. The frequency of the error is the same as the spatial frequency of the interferogram fringes, indicating that the intensity variations have not yet been completely compensated.

This data shows that a phase object has been accurately measured but that further work is required to eliminate the residual periodic phase measurement error.

References

1. C.R. Mercer, K. Creath, Optics Letters, to be published (1994).
2. P. Hariharan, B. F. Oreb, and T. Eiju, App. Opt., 26, 2504 (1987).

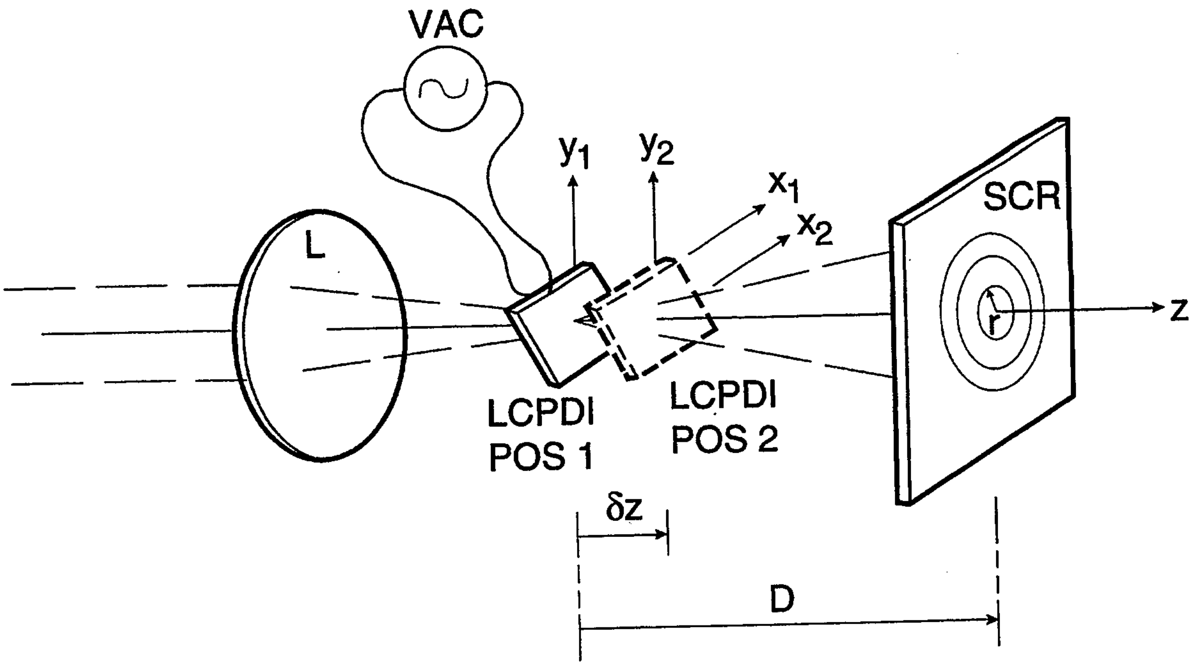

Figure 1.—Schematic of the LCPDI used to measure defocus.

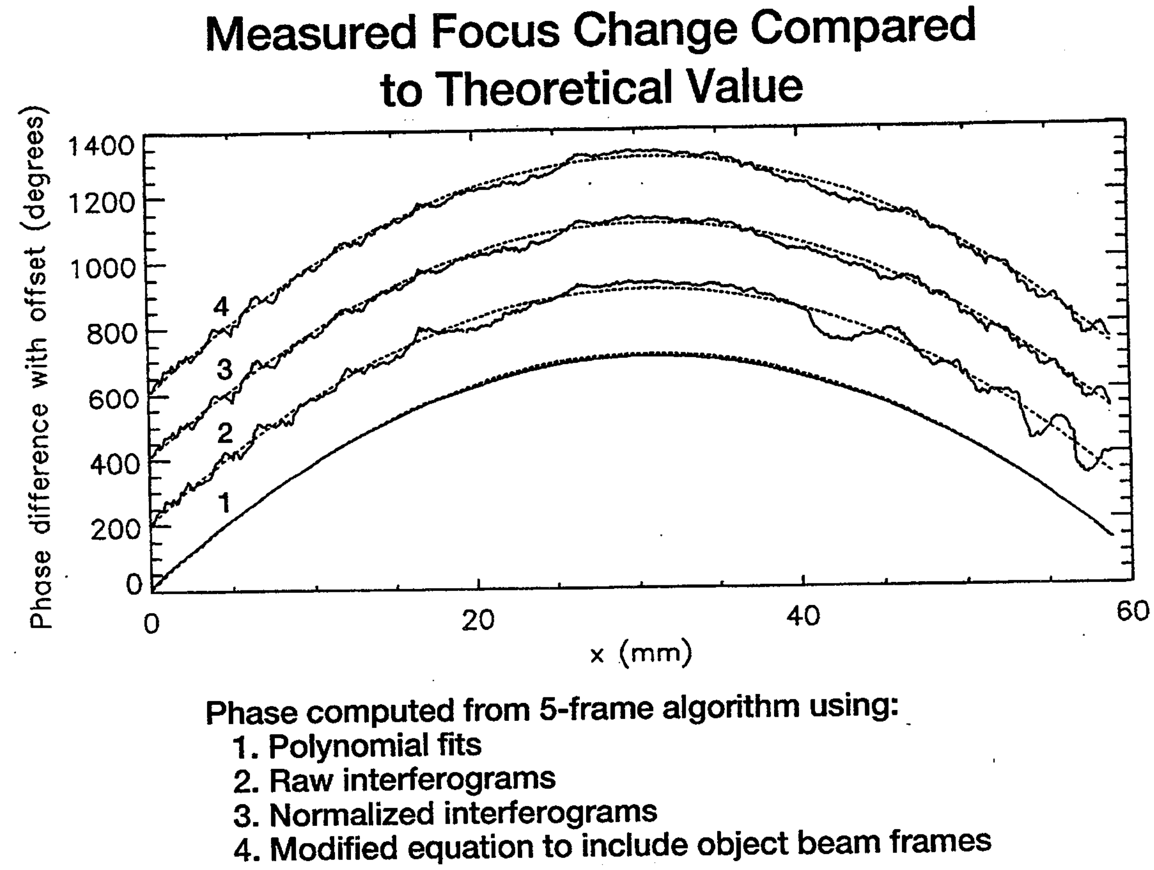

Figure 2.—Horizontal cross sections through wavefront differences calculated using various algorithms. Arbitrary offset added for clarity. Methods used (from bottom to top): (a) polynomial fits to wavefronts computed using 5-frame algorithm, (b) 5-frame algorithm, (c) interferograms normalized with object beam (Eqn. 1), and (d) phase calculated explicitly using object beam (Eqn. 2). Dashed line indicates theoretical value for the wavefront difference.

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13. ABSTRACT ***(Maximum 200 words)***

A liquid crystal PDI is demonstrated by measuring the defocus change between two positions of the interferometer. Errors caused by average intensity variations are discussed.

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