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A Phase-Stepped Point Diffraction Interferometer Using Liquid Crystals

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A phase-stepped point diffraction interferometer using liquid crystals

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ABSTRACT

A new instrument, the liquid crystal point diffraction interferometer (LCPDI), has been developed for the measurement of phase objects. This instrument maintains the compact, robust design of Linnik's point diffraction interferometer (PDI) and adds to it phase stepping capability for quantitative interferogram analysis. The result is a compact, simple to align, environmentally insensitive interferometer capable of accurately measuring optical wavefronts with high data density and with automated data reduction.

The design of the LCPDI is briefly discussed. An algorithm is presented for eliminating phase measurement error caused by object beam intensity variation from frame-to-frame. The LCPDI is demonstrated by measuring the temperature distribution across a heated chamber filled with silicone oil. The measured results are compared to independently measured results and show excellent agreement with them.

It is expected that this instrument will have application in the fluid sciences as a diagnostic tool, particularly in space based applications where autonomy, robustness, and compactness are desirable qualities. It should also be useful for the testing of optical elements, provided a master is available for comparison.

Keywords: common-path interferometer, error reduction, phase measurement algorithm, wavefront measurement, temperature measurement

1. INTRODUCTION

A new instrument, the liquid crystal point diffraction interferometer (LCPDI) has recently been described.[1] The LCPDI is based on the point diffraction interferometer.[2,3] It is made from a thin liquid crystal layer sandwiched between glass plates, with an embedded microsphere serving as the diffracting element (Figure 1). Light is reflected off or transmitted through an object of interest, and then focused onto the microsphere. The microsphere diameter is smaller than the focused spot, and so a spherical wave is generated by diffraction. The portion of the incident light unaffected by the pinhole is transmitted through the liquid crystal layer. Information contained in the incident wave is retained in this beam but filtered out of the diffracted wave. The two components of the transmitted wave are therefore referred to as the object and reference waves, respectively. They both travel coincidentally behind the LCPDI filter, and combine coherently to produce an interferogram. The object beam is attenuated by dye added to the liquid crystal layer to improve fringe contrast.

Like the point diffraction interferometer, the LCPDI has a common-path design, forming an interferogram using only a single laser beam rather than the two beams required for Mach-Zender or Michelson interferometers. This is especially important when measuring large objects like wind tunnel flows where the optical paths are very long and air turbulence must be minimized along the paths. A single beam is also advantageous when the size of the instrument must be kept small. The common-path design also requires relatively few optical elements, reducing the cost, size, and weight of the instrument, and simplifying alignment.

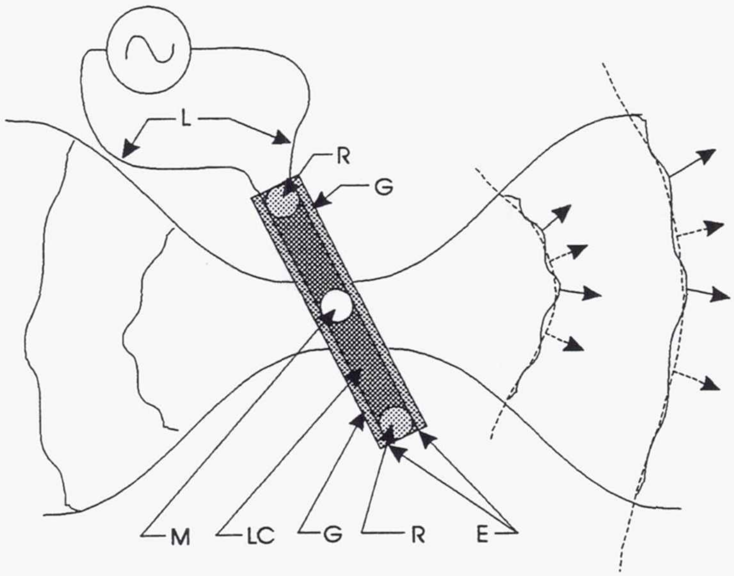

Figure 1.—Schematic of the LCPDI showing the liquid crystal layer (LC), glass plates (G), microsphere (M), spacing rods (R), electrodes (E), leads (L). The object wave is shown as a solid line, and the reference wave is shown as a dashed line.

Unlike the point diffraction interferometer, though, the LCPDI permits the use of phase shifting interferometry[4] to extract high data density, quantitative, wavefront information from the interferogram. The object beam is phase shifted by modulating amplitude of an electric field applied across the liquid crystals, altering the refractive index of the birefringent nematic liquid crystals.[5] This allows completely flexible phase stepping interferometry capability while retaining the fully common-path optical design.

For a 9 micron thick layer of Merck E-7 liquid crystals at 20 °C, a sequence of voltages ranging from 1.05 to 1.55 VAC changes the phase of an incident 514.5 nm beam by five consecutive $\pi/2$ radian steps. This permits the use of the standard 5-frame phase extraction algorithm, useful for reducing phase measurement error in the presence of phase stepping error.[6] This algorithm is appropriate for the LCPDI, because the LCPDI phase shifts a converging beam, producing a non-uniform phase shift across the image.

This sequence of applied voltages modulates the amplitude as well as the phase of the object beam because the dichroic dye molecules rotate with the liquid crystals.[7] All of the standard phase extraction algorithms assume that both the object and reference beam amplitudes remain constant from frame-to-frame, and introduce substantial phase measurement error if this condition is not met. The next section describes both a modified 5-frame algorithm that eliminates this error provided the object beam intensity variation is exactly known, and an algorithm that reduces the error with fewer computational steps. Finally, experimental data is presented that shows good agreement between a temperature distribution measured with the LCPDI and with a traversing thermocouple.

2. ALGORITHM MODIFICATION

Each recorded interferogram produced by the LCPDI can be expressed by the standard interference equation:

$$I_j(x,y) = I_j^{ref}(x,y) + I_j^{obj}(x,y) + 2\sqrt{I_j^{ref}(x,y) I_j^{obj}(x,y)}\cos\left[\frac{2\pi}{\lambda}W(x,y) + \Delta\phi_j(x,y)\right] \quad (1)$$

where j = 0,1,2,3,4, $\Delta\phi$ is the relative phase difference between the object and reference beams, I^{obj} and I^{ref} refer to the intensity of the object and reference beams, respectively, and (x,y) denotes each pixel in the image, λ is the wavelength of the incident light, and W is the object beam wavefront. If the object and reference beam intensities do not change from frame-to-frame, that is,

$$I_j^{ref}(x,y) = I^{ref}(x,y) \quad (2)$$

$$I_j^{obj}(x,y) = I^{obj}(x,y) \quad (3)$$

then the set of simultaneous equations represented by the interferograms can be solved to determine the wavefront W. One solution is the standard 5-frame phase extraction algorithm mentioned in the previous section:

$$\tan(\theta) = \frac{2(I_3 - I_1)}{(I_0 + I_4 - 2I_2)} \quad (4)$$

where $\Delta\phi_j = j\pi/2$, and $\theta = 2\pi W/\lambda$, and the explicit pixel dependence has been dropped for clarity. If, however, equation (3) is not satisfied and the object beam intensity varies from frame-to-frame, as in the case of the LCPDI, then Equation (4) must be modified to produce an exact solution.

$$\tan(\theta) = \left(\frac{\Delta I_3 - \Delta I_1}{\Delta I_0 + \Delta I_4 - 2\Delta I_2}\right)\left[\frac{\sqrt{I_0^{obj}} + \sqrt{I_4^{obj}} + 2\sqrt{I_2^{obj}}}{\sqrt{I_3^{obj}} + \sqrt{I_1^{obj}}}\right] \quad (5)$$

where $\Delta I_j = I_j - I_j^{obj}$. This equation is exact, provided that the reference beam intensity remains constant from frame to frame and that the object beam intensity distribution is known for each frame.

Since Equation (5) is requires significantly more computational steps than Equation(4), the following approximation can be used instead:

$$\tan(\theta) = \frac{2\left(I_3/I_3^{obj} - I_1/I_1^{obj}\right)}{\left(I_0/I_0^{obj} + I_4/I_4^{obj} - 2I_2/I_2^{obj}\right)} \quad (6)$$

This equation is not exact, and works best if $I_j^{obj} >> I_j^{ref}$ so that $I_j^{obj} + I_j^{ref} \cong I_j^{obj}$.

A simulated sequence of five interferograms generated from an arbitrary wavefront is shown in Figure 2. The reference beam intensity distribution is constant across each frame and does not vary from frame to frame. The object beam intensity is also uniformly distributed across each frame, but differs from frame to frame. The reference beam intensity was set to 5, and the object beam intensities were set to 20, 32, 36, 48, and 68. This sequence simulated interferograms with significant intensity modulation with poor fringe contrast. Wavefronts were computed from these five interferograms using the standard 5-frame algorithm [Equation (4)] , the approximate compensation algorithm [Equation (6)], and the exact compensation algorithm [Equation (5)]. The differences between these computed wavefronts and the synthetic wavefront used to make the interferograms are the measured errors; these are shown in Figures 3(a), 3(b), and 3(c) for Equations (4), (6), and (5), respectively. Significant periodic error is present when the 5-frame algorithm is used. This error is approximately halved when the approximate compensation algorithm is used, and completely eliminated when the exact compensation algorithm is used. The standard deviations of the computed wavefront from the synthetic wavefront for the three cases are 9.9, 1.7, and 0.0 degrees.

Figure 2.—Sequence of five simulated interferograms. $I_j^{ref}(x,y) = 5$; $I_j^{obj}(x,y) = 68$ [0.29, 0.47, 0.53, 0.70, 1.00].

3. EXPERIMENTAL RESULTS

The LCPDI was used to measure the temperature distribution across an oil-filled chamber. The rectangular chamber was constructed of four Lexan double walls with 30 millimeter diameter windows. The optical path length through the oil chamber was 43 mm, and the chamber was 60 mm high. The top and bottom of the chamber each contained a recirculating water bath to maintain the top and bottom chamber surfaces at a specific temperature. Collimated, horizontally polarized light passed through the chamber windows. A 16 millimeter diameter aperture behind the last window truncated the beam, and a 100 millimeter Cooke triplet lens focused the light, forming an f/6.3 beam. The LCPDI was mounted on a 3-axis positioner with the relaxed liquid crystal molecules lying horizontally, and was placed just behind the focused spot. The interferogram was formed on a ground glass screen and imaged onto a CCD detector array.

First, five phase-stepped interferograms were recorded to measure the wavefront passing through the chamber with the oil at room temperature (isothermal condition). Then the top and bottom chamber plates

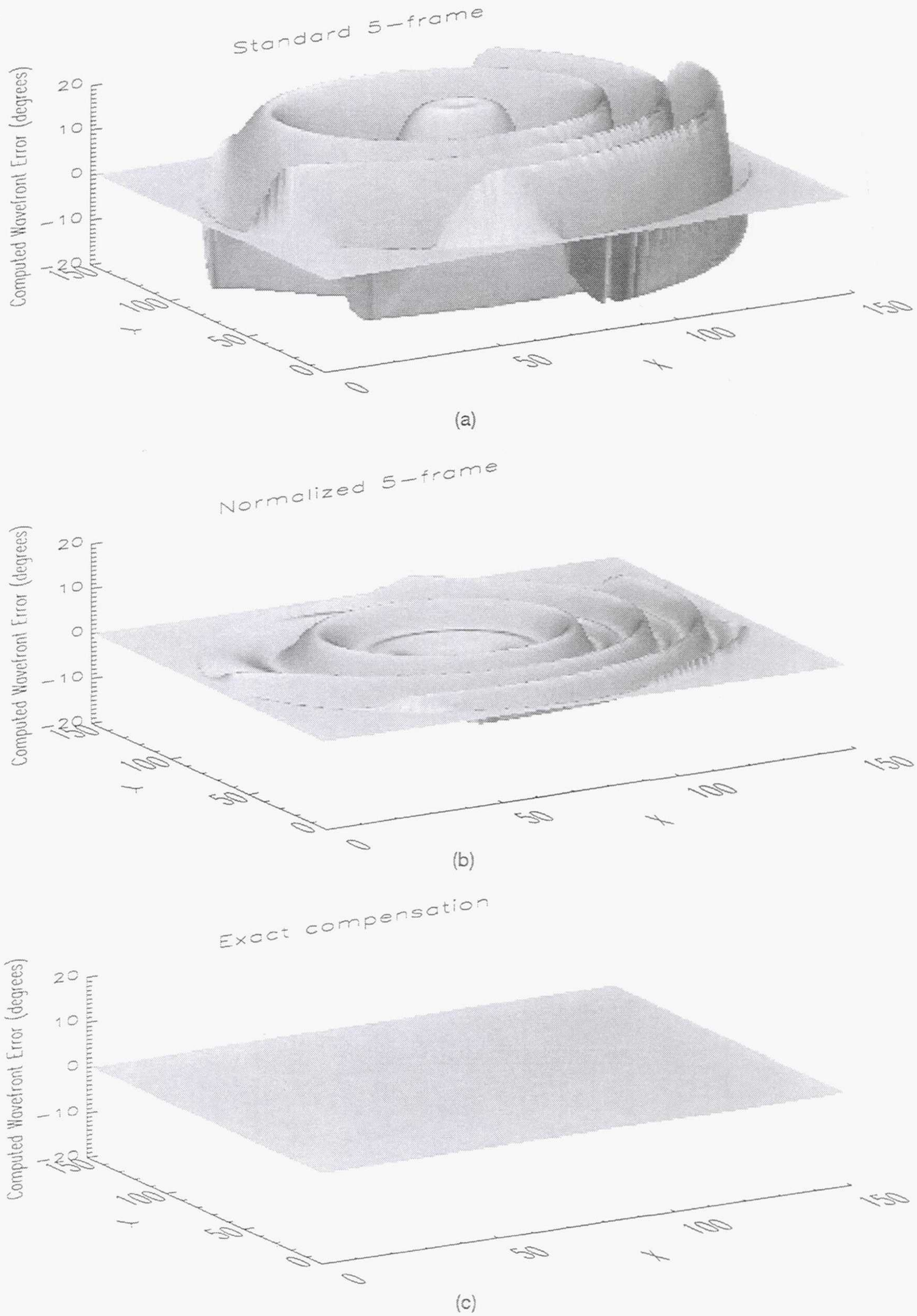

Figure 3.—Difference between synthetic wavefront and wavefronts calculated using (a) standard 5-frame algorithm, (b) approximate compensation algorithm, and (c) exact compensation algorithm.

were set to the desired temperatures and left there for about an hour to allow the oil to reach equilibrium. Five more phase-stepped interferograms were then recorded to measure the wavefront passing through the oil. The wavefront was calculated from each set of interferograms using the approximate compensation algorithm described in the previous section. In order to use this equation, the object beam intensity distribution must be obtained for each interferogram. This information can be obtained by translating the LCPDI filter so that the focused beam doesn't hit the microsphere,[8] but in this case the object beam intensity distribution was obtained by fitting a two-dimensional quadratic surface to the interferogram itself. Because the object beam intensity was much stronger than the reference beam, this was a reasonable approximation. The difference between these measured wavefronts was then used to determine the temperature distribution across the oil.

To verify the LCPDI measurement, the oil temperature distribution was also measured with a thermocouple. The thermocouple was mounted in a 0.8 millimeter diameter tube that was inserted through a small port in the top of the chamber. The tube was mounted on a traversing stage and scanned from the top to the bottom of the chamber. The temperature distribution across the oil chamber measured with both the LCPDI and the thermocouple is shown in Figure 4. Very good agreement is shown.

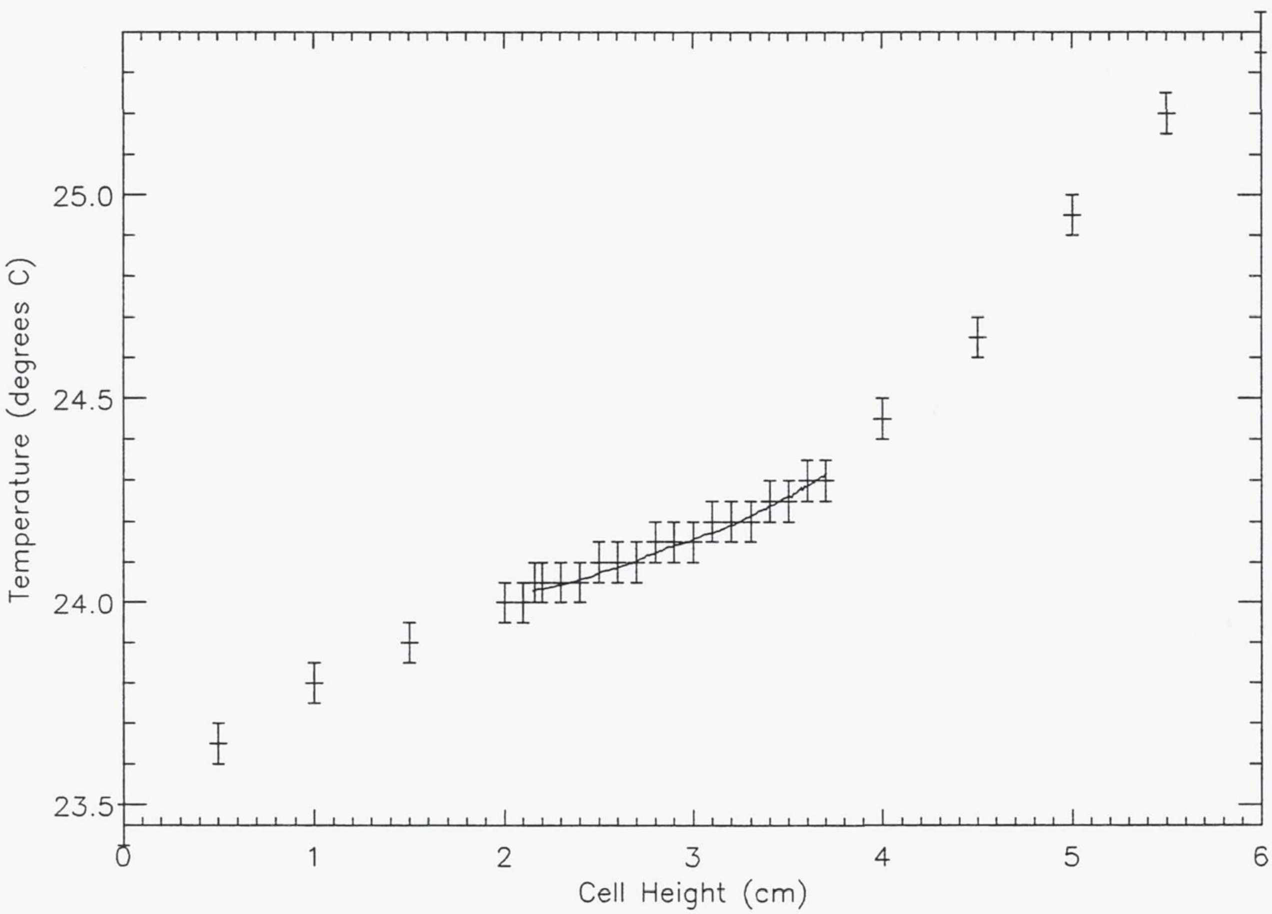

Figure 4.—Temperature measured across the oil chamber using the LCPDI (solid dots) and a thermocouple (symbols with error bars).

4. CONCLUSIONS

The effectiveness of the liquid crystal point diffraction interferometer has been demonstrated by accurately measuring the temperature distribution across an oil chamber. This demonstration shows that the LCPDI can be used as a common-path, phase-shifting interferometer for applications requiring a compact, robust, relatively inexpensive, and automated instrument.

A new algorithm has been developed to exactly compensate for object beam intensity changes from frame-to-frame. This algorithm can be used with any phase shifting interferometer where the object beam varies and the reference beam is constant.

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