Simultaneous measurement of in-plane and out-of-plane displacement fields in scattering media using phase-contrast spectral optical coherence tomography

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Received October 24, 2008; revised January 16, 2009; accepted January 20, 2009;
posted February 4, 2009 (Doc. ID 103238); published March 11, 2009

The use of phase-contrast spectral optical coherence tomography to measure two orthogonal displacement components on a slice within a scattering medium is demonstrated. This is achieved by combining sequential oblique illumination of the object and recording two interferograms before plus two after the deformation. The proposed technique is illustrated with results from a sample undergoing simple shear. Depth-resolved out-of-plane and in-plane sensitivities of 0.14 and 4.2 μm per fringe are demonstrated up to a depth of 400 μm in a water-based polymer. © 2009 Optical Society of America

OCIS codes: 110.4500, 120.5050, 120.3940.

A diverse range of techniques, including electronic speckle pattern interferometry and digital holography, provide full-field noncontact displacement maps of the surface response of components to external loads [1]. Only indirect information, however, can be obtained about the component's internal deformation state. A second family of interferometric techniques known as optical coherence tomography (OCT) has been developed since the early 1990s for imaging within weakly scattering media. Traditional OCT applications are mostly medical, and the phase data have tended to be neglected in comparison with the magnitude data, which encodes the sample microstructure [2]. The idea of combining the strengths of both families (i.e., the high displacement sensitivity of speckle interferometry with the depth-sensing capabilities of OCT) has been investigated recently by a number of authors in the field of optical metrology [3–7]. One of the most promising of these techniques is phase-contrast spectral OCT that, without any moving parts, has the ability to generate a two-dimensional (2D) tomographic image. Depth-resolved phase information encoded in the recorded data enables the evaluation of the displacement field in the depth-resolved slice. Conventional spectral OCT setups are based on coaxial illumination and observation, which only provides out-of-plane sensitivity [7]. In this Letter we present an optical system that can measure both in-plane and out-of-plane depth-resolved displacements with interferometric sensitivity within a scattering object in the same acquisition process.

Figure 1(a) shows a schematic of the optical setup. The output of a superluminescent diode (SLD) (Superlum S840-HP-I, 15 mW, central wavelength $\lambda_c = 840$ nm and bandwidth $\Delta\lambda = 50$ nm) is combined with an He–Ne laser (30 mW, $\lambda_H = 632.8$ nm), used for alignment purposes, with a 10:90 2×2 optical fiber coupler. Reference and object beams are combined with a 10:90 nonpolarizing beam splitter (BS) diffracted by a blazed grating G (grating frequency $= 1200$ lines/mm^{-1}) and detected with a 2D CCD array (Vosskühler 1300QLN, 1280×1024 pixels, 12 bit resolution). An unfolded side view of the illumination beam is shown in more detail in Fig. 1(b). This setup allows one on the one hand to illuminate the object with a light "wedge" (focused on plane xy), and on the other to image the line that results from the intersection between the beam waist and the object along one axis of the CCD sensor, denoted here as the position axis. The remaining axis on the CCD array samples different wavelengths as diffracted by the grating. A highly repeatable tilting mirror (TM) (PI piezoelectric closed loop tilt stage, S-334) is switched between two angular positions to illuminate the object from

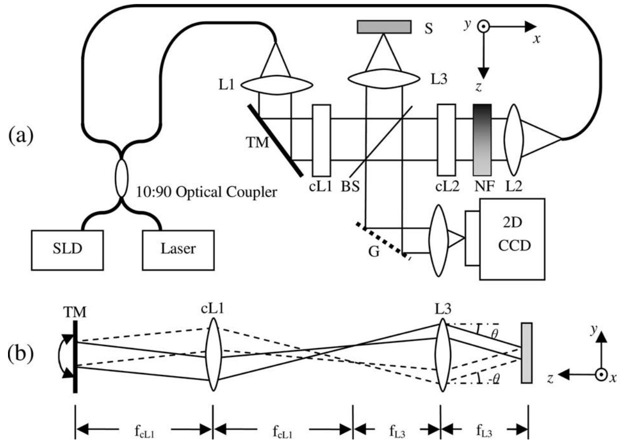

Fig. 1. (a) Top view of a phase contrast spectral OCT system for measuring displacements with dual sensitivity showing L1, L2, fixed collimators; cylindrical lenses; cL1, cL2, L3, L4, spherical lenses; NF, neutral density filter; TM, tilting mirror; BS, beam splitter; G, grating; and S, sample. (b) Unfolded side view of the illumination beam.

symmetric directions about the observation direction in the plane yz. The focal lengths of lenses cL2, L4, cL1, and L3 are 250, 150, 160, and 100 mm, respectively.

To validate the in-plane depth-resolved displacements measured with this system, a simple shear experiment was performed. The sample, S in Fig. 2, consisted of a transparent water-based polymer rubber layer with a refractive index of $n_2=1.48$ cured between two glass plates G_1 and G_2 with a refractive index of $n_1=1.51$. G_2 was fixed to a rigid support, and G_1 was displaced a known distance within its plane by using a mechanism driven by a micropositioning stage. For small deformations, the displacement field in the polymer has a constant in-plane gradient with virtually no out-of-plane component.

For oblique illumination in the plane yz at an angle θ to the z axis, the phase difference due to object deformation is [8]

$$\Delta\phi(x,y,z)=\frac{2\pi}{\lambda}[v(x,y,z)n_0\sin\theta + w(x,y,z)n_1(1+\cos\theta_r)], \quad (1)$$

where $v(x,y,z)$ and $w(x,y,z)$ are the displacements along the y and the z axes and θ_r is the angle of incidence of the refracted beam in the air/glass interface with refractive indices n_0 and n_1, respectively. By choosing equal and opposite illumination angles θ and $-\theta$, two phase differences can be evaluated, the sum of which gives the out-of-plane component $\Delta\phi_z$ and the difference of which gives the in-plane component $\Delta\phi_y$. The in-plane and the out-of-plane displacements are thus obtained as

$$v(x,y,z)=\frac{\lambda\Delta\phi_y(x,y,z)}{4\pi n_0\sin\theta}, \quad (2)$$

$$w(x,y,z)=\frac{\lambda\Delta\phi_z(x,y,z)}{4\pi n_1(1+\cos\theta_r)}. \quad (3)$$

According to Eqs. (2) and (3), with $\theta=5.7°$ and $\theta_r=3.7°$ the resulting out-of-plane and in-plane sensitivities were 0.14 and 4.2 μm per fringe, respectively. Refraction at the glass/elastomer interface changes the out-of-plane sensitivity by only 2% owing to the slight variation in refractive indices n_1 and n_2. With the object in a reference (unloaded) state, two interferograms were first recorded for each illumination direction. Two more interferograms were recorded after the shear was introduced, again for the same illumination angles. The closed-loop position control of the TM that switches illumination direction guaranteed a repeatability better than ±0.125 mrad.

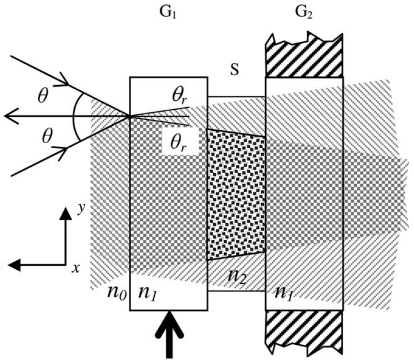

Fig. 2. Oblique illumination of polymer layer S constrained between two glass plates G_1 and G_2.

The interferograms were then processed as follows. First, the wavelength axis was converted to wavenumber $k=2\pi/\lambda$. The interferograms were then Fourier transformed along the k axis to obtain the scattering potential in the illuminated cross section in the object. The phase differences due to depth-dependent shear displacements inside the polymer were evaluated for both illumination directions from the Fourier transformed interferograms [9]. One effect of the oblique illumination is a tilt of the reconstructed cross section of the object in the yz plane, reflecting the tilt between the zero-delay reference plane and the oblique wavefronts illuminating the object. This tilt is removed by rereferencing the scattering potential corresponding to each illumination direction [8]. The out-of-plane and the in-plane phase components are then obtained by adding and subtracting, respectively, the reregistered phase differences.

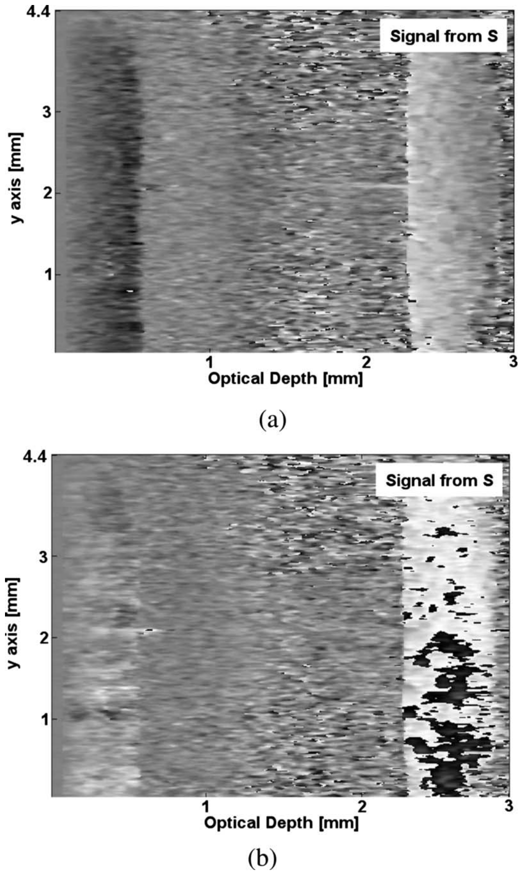

Fig. 3. (a) In-plane and (b) out-of-plane wrapped phase (black and white represent $-\pi$ and π, respectively) due to simple shear of a polymer layer sandwiched between two glass plates. The regions between 0 and 1 mm and between ~2.2 and 3 mm correspond to the cross correlation terms and to the polymer layer, respectively.

Figure 3(a) shows the in-plane wrapped phase map for the simple shear test. As expected, a linear phase profile is observed in the region between G_1 and G_2, with virtually no phase change for G_2, indicating that it remained static. Figure 3(b) shows the wrapped phase corresponding to the out-of-plane sensitivity. The thickness of the polymer layer was 400 μm, thin compared with its ~20 mm diameter in the xy plane. This reduced to a very small level the out-of-plane displacements owing to bending moments while moving G_1 along the y axis. Figure 4 shows the corresponding displacement profiles obtained by averaging the displacement fields obtained from Figs. 3(a) and 3(b) and the corresponding sensitivities for each phase component along the position axis between $y = 1.7$ and 3.7 mm for optical depth values between $z_o = 2.3$ and 2.9 mm. The range of y values chosen corresponds to the region where the illumination beams had intensity levels close to the maximum, thus resulting in a higher phase signal-to-noise ratio. The expected displacement field and its uncertainty introduced by the translation stage, 1.6 ± 0.1 μm, is indicated in Fig. 4 as two curves running from ($v = 0$ μm, $z_o = 2.9$ mm) to ($v = 1.6 \pm 0.1$ μm, $z_o = 2.3$ mm). It is observed that the measured displacements are well within the expected values. For the in-plane displacements an rms error of ~6% was found between the optical measurements and the expected average displacement profile, probably due to speckle noise and a slight nonlinearity in the displacement field gradient.

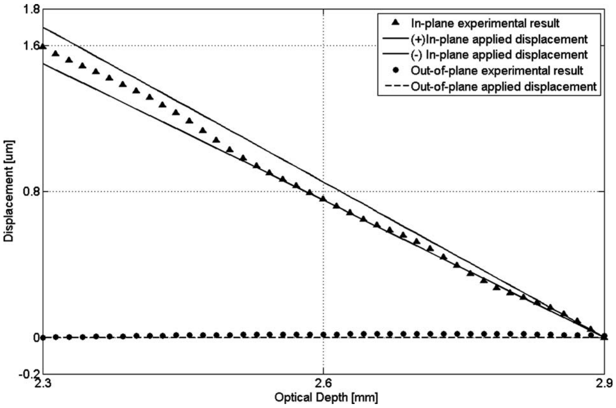

Fig. 4. In-plane and out-of-plane displacement profiles through the thickness of a polymer layer under pure shear.

In conclusion, the ability of phase contrast spectral domain OCT to measure depth-resolved displacements within a weakly scattering material was demonstrated using a system based on oblique illumination. Both in-plane and out-of-plane displacement components are obtained, as opposed to conventional OCT systems in which normal illumination can lead only to out-of-plane sensitivity.

The authors are grateful to the Leverhulme Trust and Fernando Mendoza for supporting this research and to Gustavo Galizzi for his technical assistance.

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