INSTRUMENTATION FOR BIOMECHANICAL CHARACTERIZATION OF BIOLOGICAL TISSUE BY SIMULATANEOUS COHERENT IMAGING USING COUPLED PHOTOREFRACTIVE HOLOGRAPHY AND SPECKLE SHEAROGRAPHY

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ABSTRACT

Simultaneous measurement of strain and depth-resolved imaging in soft tissue is important for complete biomechanical characterization. This can be achieved by coupling two coherent optical techniques: coherence-gated photorefractive holography and digital shearography. Whereas speckle interferometry techniques are normally used exclusively for surface material property measurements, the combination of these two techniques will allow the measurement of strain in a plane inside the material. In this work, we present initial results that validate the approach, using a long coherence length optical source and a steel plate as a test target material, as well as a diffusing cell to simulate the optical scattering of biological tissue.

Keywords:

Scattering media, photorefractive holography, biomechanics, shearography, depth-resolved imaging, speckle.

INTRODUCTION

Medical imaging for biological characterization using optical methods is a well-established and dynamic field of research [1]. Among existing imaging techniques, those using visible or near-infrared light have the advantage of being non-ionizing. With techniques such as confocal microscopy [2], Optical Coherence Tomography (OCT) [3], or photorefractive holography [4], it is possible to image a 3-dimensional volume of a biological medium with a spatial resolution in the order of a few microns or better. Ideally, complex materials such biological tissue should be characterized using multiple imaging modalities simultaneously in order to obtain information on as many material properties as possible. In theory, it is often possible to infer other types of information numerically *a posteriori* from a single type of measurement: displacement from imaging or strain from displacement, for example. In practice, however, such indirect measurements are typically noisy because of the numerical operations involved (correlation, numerical estimation of derivatives, etc.). In the case of strain, a variable of central interest in biomechanical characterization, the only direct measurement optical technique is speckle shearing interferometry [5].

We recently demonstrated the direct simultaneous measurement of both coherent imaging and strain by coupling photorefractive holography for imaging and shearography for strain measurement [6]. In the current paper, we present the characterization and performance of this coupled system.

Shearography

Speckle shearing interferometry (shearography) [7] is a full-field coherent optical technique that uses speckle (random intensity pattern produced by the mutual interference of coherent wavefronts) to measure directly the displacement gradient components across a surface. The shearographic setup used for this work is a compact inline configuration having high dimensional stability and immunity to mechanical noise [5].

Photorefractive holography

Coherence-gated photorefractive holography [4] is a full-field coherent optical technique similar, in some respects, to OCT [3] (both make use of a short-coherence light source). However, it has two advantages over the latter: firstly, OCT is generally a pointwise scanning technique whereas photorefractive holography can image a full plane in a single acquisition. Secondly, since the photorefractive effect is only sensitive to the gradient of optical illumination, incoherent light (i.e. non-ballistic photons which are not involved in interference) does not contribute to the hologram recording process [8]. Hence the photorefractive medium naturally filters out background scattered light which would otherwise decrease the signal-to-noise ratio as with other coherent techniques such as OCT. Figure 1 shows a typical holographic image obtained with the setup.

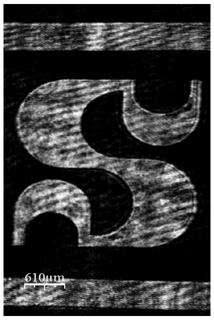

Fig. 1: Hologram obtained with the holographic interferometer (Université de Sherbrooke logo made from an etched chromium film on a glass substrate).

Note that the experiments presented here aim to validate the fundamental principle of the instrument, namely *imaging through an optically diffusing medium using the combination of photorefractive holography and shearography*, a procedure most efficiently accomplished with a long coherence length light source. The target used in the experiments was a steel plate, preceded by an optical diffusing cell. Future experiments carried out with a short coherence length source will then make use of *coherence-gated* photorefractive holography for optical sectioning within the material.

IMAGING THROUGH TURBID MEDIA

Experimental details

The instrument (Fig. 2), which uses a linear polarized frequency-doubled Nd:YAG laser at *532 nm*, is comprised of two sub-systems: a photorefractive holography interferometer (top) and a shearographic interferometer (bottom) [6]. When the sample under study has an optically rough surface, the light field emerging from the holographic interferometer will be a speckle pattern. Therefore, this “holographic speckle field” can be used for speckle interferometry by the second stage, the digital speckle shearing interferometry. Note that the light emerging from the holographic interferometer is Transverse-Magnetic (TM) mode polarized. A half-wave plate is required between the holographic and shearing interferometers in order to rotate the polarization by 45° and thus inject equal amounts of Transverse-Electric (TE) and TM-polarized light into the shearing interferometer.

A first hologram of the object in a reference state is recorded, requiring 45 s to record the hologram into the SBN:61 crystal. Next, the signal-beam shutter is switched off and the four shearograms required by the 4-step phase-shifting algorithm [5] are recorded using a digitally-controlled Liquid Crystal Variable Retarder (LCVR). The acquisition of the four shearograms required 0.3 s in all, which is faster than the hologram erasure time (1 minute under constant illumination).

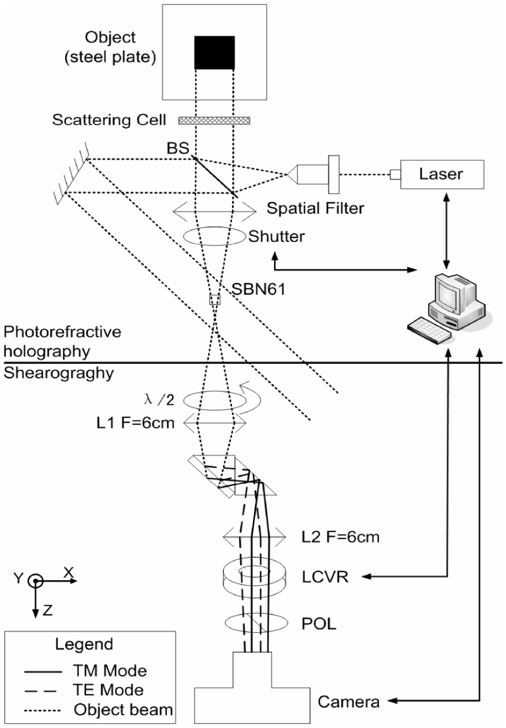

Fig. 2: Schematic of the coupled experimental setup: photorefractive holography (top) and speckle shearing interferometer (bottom).

Subsequently, the steel plate was centrally loaded and a second hologram was recorded into the crystal, followed by the acquisition of the required four phase-shifted shearograms with the LCVR. Finally, the wrapped differential phase maps shown in Fig. 3 were obtained with the four-step algorithm.

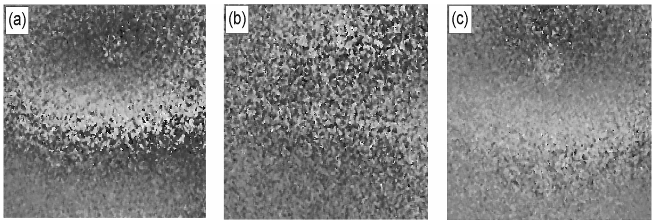

Fig. 3: Three sheared holograms (5x5 median filtered) obtained with the coupled system: (a) without scattering cell, hologram recording time of 120 s, (b) with scattering cell OD=0.288, hologram recording time of 120 s, (c) with scattering cell OD=0.288, hologram recording time of 300 s.

Results

A 7.5 x 10 mm^2 area of the steel plate around the loading point was imaged by the system. Phase maps determined from the sheared holograms obtained both without the scattering cell and with the cell (611 nm spheres suspended in water OD=0.3 at 532nm) for two different hologram recording times are shown in Figs. 3a, 3b, and 3c.

A quantitative analysis of phase map degradation as a function of optical density was undertaken. As the phase maps depict fringes, the optical parameter chosen to show a degradation of the image is the contrast [9], *C*, of the fringes:

$$C = \frac{\langle I_{\max} \rangle - \langle I_{\min} \rangle}{\langle I_{\max} \rangle + \langle I_{\min} \rangle} \tag{1}$$

where $\langle I_{\max} \rangle$ and $\langle I_{\min} \rangle$ are average intensity values determined at the fringe maxima and minima, respectively.

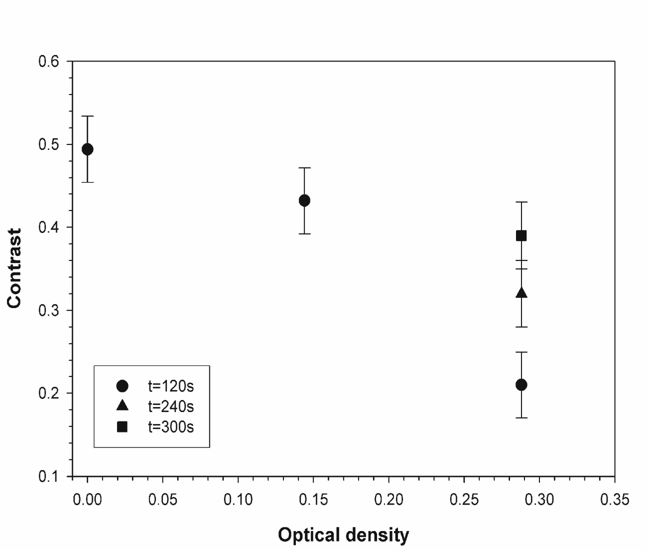

Fig. 4: Contrast of the shearographic fringes recorded by the coupled system versus optical density for different scattering samples (silica spheres in distilled water, *diameter=611 nm*) and with the same scattering cell (*OD=0.288*) for different recording times of the holograms.

By comparing Figures 3b and 3c, it is apparent that fringe contrast increases with hologram recording time. In addition, the graph in Fig. 4 shows that fringe contrast *increases* with increasing optical density. This result is rather surprising. Indeed, the fringe contrast, when using shearography alone without photorefractive holography as a front end, rapidly falls to zero with increasing optical density of the diffusing medium [10], due to the loss of coherence caused by light passing through the diffusing medium.

In our case, however, when combining shearography with photorefractive holography, ballistic photons, travelling through and minimally affected by the turbid medium, accumulate coherently in the photorefractive medium, thus increasing contrast with longer hologram recording times. In addition, as explained previously, the crystal acts as a filter for the diffuse scattering light background. As a consequence, the signal-to-noise ratio is highly enhanced and, given a long enough recording time (e.g. 300 s with OD=0.288), the fringe contrast may become nearly as good with the scattering cell as without the cell.

CONCLUSION

In conclusion, we have demonstrated the capability of a system consisting of photorefractive holographic interferometer and a speckle shearing interferometer for simultaneous coherent imaging (holograms) and strain field measurement. In addition, results characterizing system performance according optical density of the diffusing media were presented. .

These results suggest that, using a short coherence optical source, this technique could be used to measure planar strain fields inside the material via optical sectioning, while simultaneously recording coherent images of the material plane under study.

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