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Tomographic imaging of all orthogonal components of the displacement field in weakly scattering materials using wavelength scanning interferometry

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ABSTRACT

This paper presents a wavelength scanning interferometry system which provides displacement fields inside the volume of semi-transparent scattering materials with high spatial resolution and three-dimensional displacement sensitivity. This technique can be viewed as frequency multiplexed swept-source OCT in which different channels carry information for specific displacement sensitivities.

Keywords: wavelength scanning interferometry, depth-resolved measurements, phase tomography, displacement tomography, strain tomography.

1. INTRODUCTION

Experimental mechanics is currently contemplating tremendous opportunities of further advancements thanks to a combination of powerful computational techniques and also full-field non-contact methods to measure displacement and strain fields in a wide variety of materials. Identification techniques, aimed to evaluate material mechanical properties given known loads and measured displacement or strain fields, are bound to benefit from increased data availability (both in density and dimensionality) and efficient inversion methods such as Finite Element Updating (FEU) and the Virtual Fields Method (VFM)[1]. They work at their best when provided with dense and multicomponent experimental displacement (or strain) data, i.e. when all orthogonal components of displacements (or all components of the strain tensor) are known at points closely spaced within the volume of the material under study. Although a very challenging requirement, an increasing number of techniques are emerging to provide such data. In the realm of optical techniques, strain measurement is usually performed either by numerical differentiation of direct measurements of displacement fields or by using the photoelastic effect. While in the first case internal features of the material are tracked (either using phase measurements or image correlation approaches), in the second, techniques rely on the retardation between different polarization components as light propagates through a transparent material that shows transient birefringence when loaded. Polarisation sensitive OCT relies on the photoelastic effect to measure strains but it also provides depth-resolved distributions of birefringence (due to tissue fibre orientation), optical axis orientation and phase retardation [2]. It is effectively a type of reflection mode photoelasticity that uses scattered light, with the ability to image structures and features within the volume of scattering materials with exquisite detail. However, it only provides the difference between the in-plane principal strain components. Due to the normal illumination/observation configuration, out-of-plane displacements can also be evaluated from the phase change due to mechanical deformation. A family of related techniques has recently emerged with the ability to measure displacement fields inside the volume of scattering materials without requiring birefringence.

These techniques include: 1) Phase contrast spectral OCT (PC-SOCT), based on a broadband source and spectral detection and used to map out-of-plane displacements [3, 4]; 2) Tilt scanning interferometry (TSI), based on a monochromatic source and a tilting illumination beam and used to map 3-D displacement fields with one in-plane and out-of-plane sensitivity [5, 6]; 3) Wavelength scanning interferometry (WSI), which relies on a tunable laser and was used to measure out-of-plane depth resolved displacements of a stack of optically smooth and also speckled wavefronts [7, 8]. Recently, a full sensitivity WSI system was proposed to measure all components of the displacement in the volume of semitransparent scattering materials [9], of which a summary is offered here.

1. WORKING PRINCIPLE AND RESULTS

Figure 1 shows a top view of the optical setup. The light source consists in a mode hop free tunable laser, TL (TSL-510 Type A, Santec Ltd.) which can scan the wavelength from 1260 to 1360 nm in steps as small as 0.011 nm. The laser is connected via a single mode optical fibre (SMF) to a 2×4 fibre optic splitter that divides power equally between the four output channels into single mode fibres.

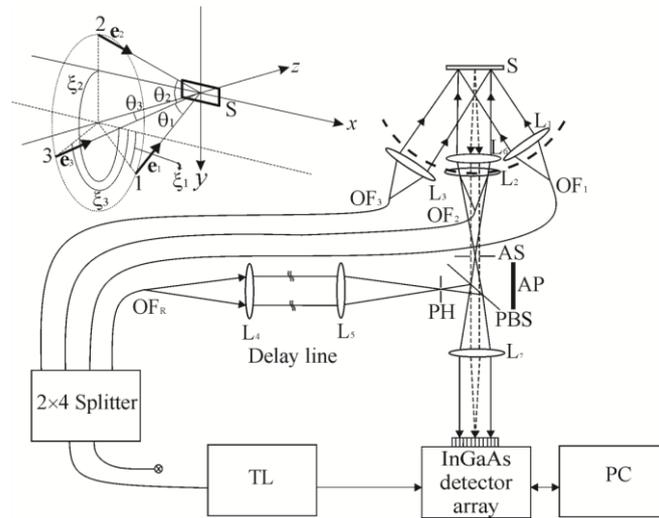


Figure 1. WSI set-up and illumination configuration (top left insert).

One output channel, OF_R , feeds the reference arm of the interferometer whilst the other three, OF_1 , OF_2 and OF_3 , provide three illumination beams collimated by near-infrared double achromats L_1 , L_2 and L_3 and arranged so that they illuminate the sample, S , from three non-coplanar directions (see insert in Fig.1). Upon scattering on sample S , reference and object beams are combined with a pellicle beam splitter (PBS) and detected with a near-infrared InGaAs photodetector array (SU640SDV-1.7RT/RS170, Goodrich Corporation, 640×512 pixels, 14 bit). Sequences of two-dimensional interferograms are recorded while the frequency of the laser is tuned at a constant rate. Each pixel thus records an intensity signal which temporal frequency encodes the optical path difference between the illumination and reference beams for a particular point on the sample. Fourier transformation along the time axis reconstructs the magnitude and phase of the material's microstructure. In order to prevent data overlap in the frequency domain, the reference beam optical path is adjusted with a delay line, while those of the object beams are adjusted by positioning collimating lenses L_1 , L_2 and L_3 at slightly different distances from the sample. Different optical paths along each illumination direction are required in order to separate or multiplex, in the frequency domain, the signals corresponding to each sensitivity vector. In this way, all the information required to reconstruct the location and the 3D

displacement vector of scattering points within the volume in the material is recorded simultaneously. Experiments consisting of controlled rigid body rotations and translations of a phantom were performed to validate the results. Both in-plane and the out-of-plane displacement components were measured for each voxel in the resulting data volume, showing an excellent agreement with the expected 3-D displacement –see Fig.2.

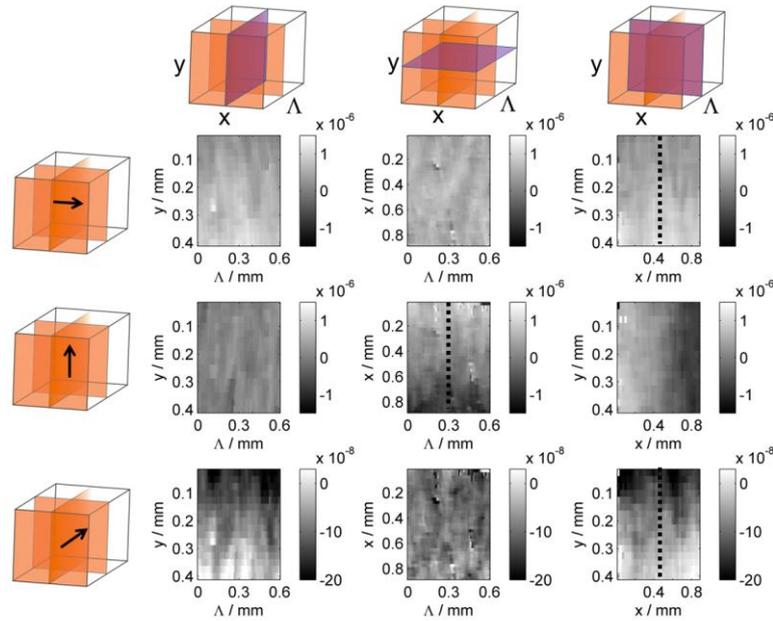


Figure 2. Cross sections of the measured 3-D displacement field corresponding to a rigid sample under in-plane rotation and out of plane tilt. The rows indicate the displacement components u , v and w along the x , y and z axes, respectively. The columns show different sections of the data volume: planes $y\Lambda$, $x\Lambda$ and xy , with Λ being optical path along z . Displacements units: m.

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