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Towards the identification of spatially resolved mechanical properties in tissues and materials: State of the art, current challenges and opportunities in the field of flow measurements

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Our ability to predict the mechanical behaviour of materials, components and even tissues and organs is only as good as the knowledge we have about their internal structure, the spatial distribution of their properties, and the boundary conditions that constrain and drive their deformation. This talk will present state of the art advances in the measurement of internal structure and 3D deformation fields in engineering materials and tissues, and their use to identify 'spatially dependent' mechanical properties with a combination of novel optical coherence tomography systems and inversion algorithms.

Neutron diffraction, X-ray tomography, Magnetic Resonance Imaging and Optical Coherence Tomography are all examples of techniques with the ability to map 3-D strain in the bulk of solid materials. They differ in spatial resolution, strain resolution, and type of materials that can be studied. This work is focused on optical methods and different approaches will be presented, including recent developments in phase contrast wavelength scanning interferometry and a combination of optical coherence tomography and digital volume correlation to estimate elastic properties of synthetic phantoms and porcine corneas [1-3].

Inversion algorithms based on finite elements and the Virtual Fields Method (VFM) are used to extract mechanical properties from the knowledge of the applied loads, geometry and measured deformation fields. The VFM is based on the principle of virtual work and retrieves the constitutive parameters by utilizing full-field deformation measurements [4]. This method is more effective than Finite Element Updating in terms of computation time since for the latter an FE model needs to be created and updated iteratively. The VFM has been applied successfully to the identification of constitutive parameters for linear elastic materials such as composites, elasto-plasticity for metals as well as hyper-elasticity for soft and biological materials such as artery walls.

The measurement of 3-D displacement and strain using phase contrast OCT faces a number of challenges, including: 1) dispersion, i.e. variation of refractive index with wavelength, which impairs the depth resolution; 2) refraction effects, which lead to spurious strains and require refraction compensation to re-map the internal structure in a regular grid from which strain can be evaluated from displacements; 3) 3-D phase unwrapping, i.e. the process of finding the right multiple of 2π in the wrapped phase distributions obtained with phase-contrast techniques. This is a difficult problem in 3-D as phase singularity loops, which are common in experimental data, lead to phase unwrapping errors that propagate through the data volume; 4) the extension of the Virtual Fields Method to 3-D; the study of its applicability to identification and the effect of noise in the measured displacements. Also, there are interesting approaches that are emerging to study the 2-D spatial distribution of modulus in the case of known and unknown boundary conditions [5].

Current efforts into extending these OCT methods into single shot techniques have the potential of expanding the range of applications to study dynamic events such as micro-flows in engineering and biological systems in which scattering particles are transported in a flow (e.g. tribology, microfluidic devices, cell migration, multi-phase flows, etc). Proof of principle systems are currently limited to a spatial resolution of ~40×40×40 independent measurements. Temporal resolution depends on light source power and sensitivity of the 2-D photodetector array used, but can be expected to range between a few tens to a few hundreds of volumes per second.

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