Phase-contrast optical metrology for depth-resolved corneal deformation measurements

Pablo D. Ruiz

Manuel de la Torre-Ibarra and Jonathan Huntley

1 Wolfson School of Mechanical and Manufacturing Engineering
   Loughborough University

2 Centro de Investigaciones en Óptica, León, Guanajuato, Mexico.
Outline

- Surface interferometry limitations
- Optical coherence tomography to image internal microstructure.
- New method that combines both worlds.
- Displacement fields through a cross section of a porcine cornea
- Comments on experimental challenges, corneal structure and phantoms towards identification of depth-resolved modulus
Surface interferometry

- Only surface displacements are obtained.
- Internal structure and strains difficult to estimate through inverse problem methods.
Optical coherence tomography

Structure and deformation

**Structure**

Optical Coherence Tomography

- Structure through the thickness

Deformation

Interferometry

- Optical phase based
- High sensitivity (~10nm)
- Surface measurements
Spectral Optical Coherence Tomography

Depth-resolved displacement measurement

[M de la Torre-Ibarra, P D Ruiz and J M Huntley (2005), Opt. Exp. 14:9643-9356]
Refractive surgery / corneal biomechanics

- 1.8m operations in 2001 in US alone
- 5-20% have residual refractive errors
- Significant requirement to measure internal mechanical properties of cornea

Images from JirehDesign and Capio Eye
Depth-resolved corneal deformation

\[ \delta z = \gamma \frac{\lambda_c^2}{\Delta \lambda} \]
\[ \Delta z = \frac{N \lambda_c^2}{4 \Delta \lambda} \]

[M de la Torre-Ibarra, P D Ruiz and J M Huntley (2005), Opt. Exp. 14:9643-9356]
Case study: Depth-resolved corneal deformation

Out-of-plane sensitivity
Sources of phase change

• Motion of scattering centres

• Surface curvature

• Photoelastic effect \( n = n(\text{strain}) \)

• Non-uniform refractive index \( n = n(x,y,z) \)

• Dispersion \( n = n(\lambda) \)
Phantoms: start with something known

Collagen lamellae in the mid-stroma

Orientation of collagen fibrils in adjacent lamellae of the corneal stroma

[Meek and Fullwood (2001), Micron 32:261]
[Fullwood (2004), Structure 12:169]
Phantoms: artificial corneal trephination

- Dimensions from Arizona’s eye model
- Silicone rubber to match corneal effective modulus (0.1-0.9 MPa) at normal IOP
- Monolayer and bilayer (0.55 and 1.88 MPa)
- Bilayer with low and high moduli
- Inflation test to find pressure vs. apex displacement
Phantoms: artificial anterior chamber

- Known geometry, boundary conditions, loads and material properties
- Used to validate experimental technique and test inverse methods
Corneal rise vs. ‘intraocular’ pressure

- Cornea MM282 Top Layer (Low E)
- Human Cornea (Anderson et al, 2004)
- Cornea MM240-TV Top Layer (High E)
- Normal IOP
Summary: Phase Contrast OCT

- Single-shot structure + depth-resolved deformations
- Displacement sensitivity 100-1000 times higher than depth-resolution
- Potential to estimate mechanical properties within the material
- Phantoms developed for validation

~0.05mm

Displacement sensitivity
~ $\lambda/20$

~1mm

~10mm
Thank you for your attention