THE UNIVERSITY OF UTAH

Developing a Photoelastic Sensor to Measure Skin Friction in Turbulent Boundary Layers

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Overview

Why measure wall shear stress in turbulent flows?

- Contributes significantly to both drag and noise[a]
- Skin friction can be used to solve for flow characteristics in full-scale *in-situ* tests
- Turbulence causes variance in both space and time

What is the challenge? Shear stresses are small:

$$\tau = \mu \frac{dU}{dz} \leftarrow \delta \approx \frac{.37x}{Re^{1/5}} \text{ and } \frac{dU}{dz} \approx \frac{U_\infty}{\delta} \quad (1)$$

For water at 1 m/s, $\tau_{avg} \approx 0.01\text{Pa}$. Given fluctuations around 30%[b], we need a resolution of ±0.003 Pa

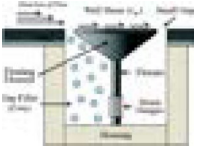
[a] Perlin, Dowling, and Ceccio 2016.
[b] Keirsbulck, Labraga, and Gad-el-Hak 2012.

Current Limitations

Available techniques for evaluating shear stress:[1]

Technique	Pros	Cons
Oil Film Interferometry	Accurate ±1%	No Spatial Resolution
Floating Element[2,3,4]	Direct Measurement	Internal Frequency Response
Particle Tracking (PIV,MTV)	Resolved Δx, Δt	Indirect, Limited to Low *Re*

(a) Oil Film Interferometry

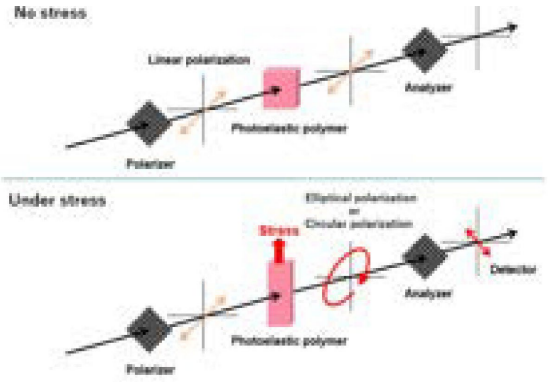


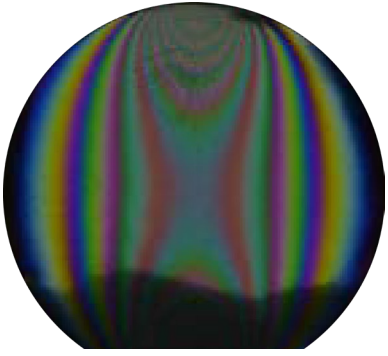
(b) Floating Element

(c) PIV

[1] Örlü and Vinuesa 2020.
[2] Baars et al. 2016.
[3] McLaughlin, Lawson, and Ganapathisubramani 2023.
[4] Meritt et al. 2017.

What is Photoelasticity?





Why Photoelasticity?

- Demonstrated Spatial Resolution[5]
- Demonstrated Sensitivity[6,7]
- Demonstrated Potential[8]

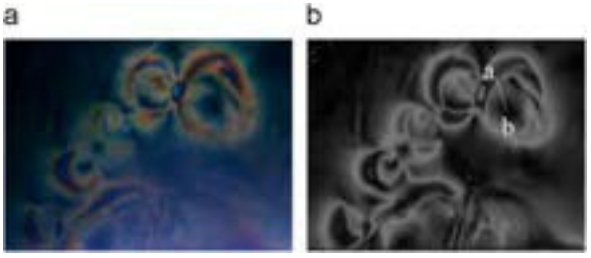


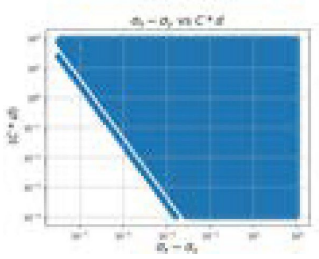
Figure: Loading Under Foot Induced Stress

[5]Dubey and Grewal 2010.
[6]Mukashev et al. 2022.
[7]Mitsuzuka et al. 2021.
[8]**mclaughlin˙measuring˙2024.**

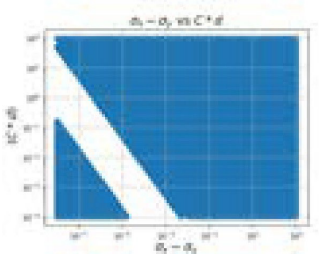
Constraining Factors

$$I = I_0 \sin^2 \frac{\pi d C}{\lambda} (\sigma_x - \sigma_y)$$

I	Light Intensity
C	Photoelastic Constant
d	Optical Path Length
λ	Light Wavelength
$(\sigma_x - \sigma_y)$	Difference in Principal Stress Axes



(a) I=1



(b) I=0

Figure: Windows where the Photoelastic Effect can be observed for $\lambda = 520$ nm

Experimental Approach

1. Demonstrate Proof of Concept
2. Quantify Photoelastic Response
3. Perform Measurements for Known Experimental Flows
4. Demonstrate *In-Situ* Measurements

Sensor Parameters

There are several control variables that dictate the performance of a sensor:

- Material
  - Young's Modulus (E)
  - Photoelastic Constant (C)
- Thickness of Sensor (t)
- Transmission vs Reflection

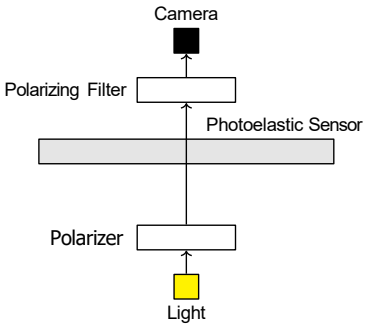
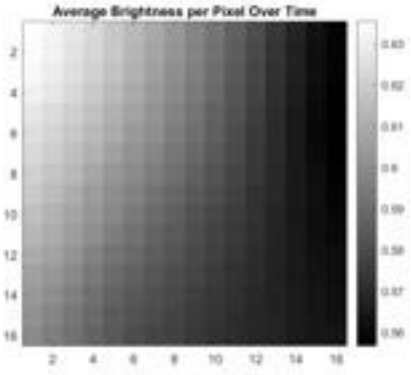
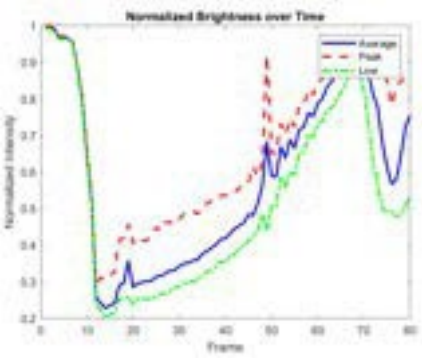


Figure: Experimental Optics

Preliminary Results





Future Work

- Confirm that signal amplification is observed for reflection photoelasticity
- Establish a database of photoelastic material parameters
- Confirm resolution of stress components using static loading
- Perform shear stress measurements for laminar flow
- Perform shear stress measurements for turbulent water channel flow
- Perform *in-situ* experimental measurements of atmospheric or vehicular flows