Instrumentation-Grade Shear Stress Sensors for Direct Measurement of Mean and Fluctuating Skin Friction

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*Presenter
Outline

• Motivation and Background
  • Wall shear stress – what is it and why do we care?
  • Current measurement techniques

• Sensor Development

• Test and Calibration

• Summary
Wall shear stress

- Wall shear stress results from molecular interactions at fluid-solid interface
  - No-slip condition
- On continuum scale can view as point force vectors proportional to velocity gradient
- Why measure wall shear stress?
  - Fundamental fluid measurements
  - Friction velocity value needed for normalization of boundary layer data
  - Quantify drag mitigation efforts
  - Feedback in flow control applications

\[ \tau_w = \mu \left. \frac{dU}{dy} \right|_{y=0} \]
Measurement techniques - indirect

- Wall shear stress estimate based on correlation from other measured quantity
- Pressure drop
  - Preston tubes, Stanton tubes, razor blades, fences
- Velocity profile
  - Hotwire, Pitot probe, Optical (PIV, LDV, etc)
- Thermal transfer
  - Hotfilm

- Difficulty with resolution
- Require extensive calibration
- Applicable to subset of flows
Measurement techniques - direct

- Physical displacement of element due to shear stress
  - Pros:
    - Direct Measurement
      - No correlation needed
    - No in-situ calibration needed
  - Directional Measurement
  - Cons:
    - Alignment
    - Fragile
    - Gaps collect debris
- Transduction types
  - Optical
  - Piezoresistive
  - Capacitive

Currently no direct time resolved measurement tool available for complex 3-dimensional flows
Our Approach

• OUR TECHNOLOGY
  • MEMS-based, floating-element capacitive shear stress sensor
  • Thermally compensated, robust sensor package
  • Optimized interface circuitry for high dynamic range and bandwidth

• BENEFITS
  • Simultaneous mean & fluctuating measurements
  • Time-resolved, direct measurement of shear stress
    – Does not require unique calibration to heat transfer
    – Improved accuracy and reduced uncertainty
  • High temporal (> 5 KHz BW) & spatial resolution (< 1mm)
  • Non-intrusive, can mount flush to test models and wind-tunnels for minimal flow disturbance and impact
Outline

• Motivation and Background
• Sensor Development
  • Design
  • Sensor Fabrication
  • Packaging
• Test and Calibration
• Summary
System Overview

• Components
  • Capacitive shear stress sensor
  • Sensor packaging
  • Interface circuitry
CSSS Transduction

- Capacitive based, floating element shear stress sensor
  - Interdigitated capacitive comb fingers
  - Electrical connections achieved via wire-bonds
    - Through silicon vias (TSVs) approach is currently in development
CSSS Operation

- Flow displaces floating element
- Fingers create parallel plate capacitors
- Gaps between fingers change
- Results in change in capacitance

• Capacitance Measurement
  • $V_{\text{bias}} \rightarrow$ sensor acts as impedance bridge
    • Impedance of capacitor at dc $\rightarrow$ doesn’t exist
    • Need add frequency content for dc sensing

• Modulate output of sensor
  • Bias frequency

• Demodulate signal
  • Recover baseband signal
Interface Circuitry

• Function
  • Provides modulated bias voltages to the capacitive sensor
  • Powers the buffer amp
  • Demodulates the signal from the sensor
  • Outputs the signal to DAQ

• Circuits are tuned and calibrated with an assigned shear stress sensor package
• **Package Description**
  • Shear stress sensor wire-bonded to PCB endcap
  • Stainless steel cylindrical housing
    • 0.5” diameter x 2” long
  • Recessed area in housing for PCB
  • Laser micromachined shim cap
Outline

• Motivation and Background
• Sensor Development
• Test and Calibration
  • Calibration
    • Static
    • Dynamic
  • Wind Tunnel Testing
    • Setup
    • Results
• Cable Testing
• Environmental Testing
• Summary
Characterization – Mean shear stress

- Flow cell: assumption of fully developed incompressible two-dimensional Poiseuille channel flow with linear pressure gradient
- Adjust shear range with shim height and mass flow controller

\[ \tau_w(y = 0) = \frac{h \, dP}{2 \, dx} \]
Characterization – Dynamic shear stress

- Acoustic plane wave tube
- Compression driver establishes standing wave pattern
- Sensor placed at velocity (and shear) maxima, pressure minima
- Reference microphone in termination

\[ \tau_w(\omega = 2\pi f_{test}) = -\frac{1}{c} \sqrt{j\omega \nu} \tanh\left( a \frac{j\omega}{\nu} \right) \left( e^{jkd} - Re^{-jkd} \right) \frac{e^{jk(d-\delta)} - Re^{-jk(d-\delta)}}{P_{measured}} e^{j\omega t} \]
Sensor Calibration

- Ran 6 full sensor systems through full calibration procedures
  - Sensitivity, noise floor, resonant frequency, drift, offset

<table>
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<tr>
<th>Parameter</th>
<th>Units</th>
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<th>2</th>
<th>3</th>
<th>4</th>
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<tbody>
<tr>
<td>Dynamic Sensitivity @ 1.128 kHz</td>
<td>[mV/Pa]</td>
<td>2.54</td>
<td>3.09</td>
<td>1.93</td>
<td>3.07</td>
<td>2.89</td>
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<td>Nominal dc Offset</td>
<td>[mV]</td>
<td>62</td>
<td>142</td>
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<td>Resonant Frequency</td>
<td>[kHz]</td>
<td>2.9</td>
<td>3.1</td>
<td>3.6</td>
<td>3.3</td>
<td>3.5</td>
<td>3.8</td>
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<tr>
<td>Noise Floor @ 1.128 kHz</td>
<td>[µV/rtHz]</td>
<td>2.1</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
<td>0.9</td>
<td>0.3</td>
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<tr>
<td>Minimum Detectable Shear Stress</td>
<td>[µPa/rtHz]</td>
<td>826.8</td>
<td>97.1</td>
<td>155.4</td>
<td>65.1</td>
<td>311.4</td>
<td>135.1</td>
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<tr>
<td>Mean Drift per ½ hour</td>
<td>[mV]</td>
<td>±0.4</td>
<td>±0.3</td>
<td>±0.7</td>
<td>±0.4</td>
<td>±0.3</td>
<td>±0.8</td>
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</table>
Wind Tunnel Setup

• 6 sensor systems installed in NASA LaRC Shear Flow Wind Tunnel for testing
  • 20” x 28” cross section
  • Well characterized skin friction values
• Sensors compared against Preston tube data
• Collected static and dynamic data

• Sensor System 5
• Sensor System 5
20” x 28” Wind Tunnel Results

• Sensor System 5
  • Compared with NASA Preston Tube data

![Graph showing shear stress vs tunnel speed for Sensor 5 with data points and a Preston Tube line.

- Shear Stress [Pa]
- Tunnel Speed [m/s]
- Data points labeled Rising U and Descending U with error bars.
- Preston Tube line.

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Cable Test

• Post Wind Tunnel Test
  • Cable at output of circuit instead of between circuit and sensor head (based on feedback)
  • RG-58 cable
  • Experimental results using sensor system 2

<table>
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<tr>
<th>Cable Length [ft]</th>
<th>5</th>
<th>25</th>
<th>50</th>
<th>62</th>
<th>75</th>
<th>100</th>
<th>120</th>
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<tr>
<td>dc Offset [mV]</td>
<td>143.3</td>
<td>143.8</td>
<td>143.9</td>
<td>144.1</td>
<td>144.2</td>
<td>144.2</td>
<td>144.2</td>
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<tr>
<td>Sensitivity [mV/Pa]</td>
<td>3.19</td>
<td>3.20</td>
<td>3.19</td>
<td>3.20</td>
<td>3.19</td>
<td>3.19</td>
<td>3.20</td>
</tr>
</tbody>
</table>
Environmental Test

- Espec Environmental Chamber
  - Temperature 20 °C to 50 °C
  - Humidity: 80% to 90%
Outline

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Summary

• Calibrated results (typical)
  • Shear stress sensitivity: 2.9 mV/Pa (@1.128 kHz)
  • Resonant Frequency: 3.5 kHz
  • Pressure Rejection Ratio: 72 dB
  • Noise Floor: 0.9 μV/Hz$^{1/2}$
  • Minimum Detectable Shear Stress: 0.3 mPa
  • Dynamic Range: > 76 dB (limited by test setup)

• Sensors have also been tested in multiple flow facilities
  • Grazing flow impedance duct (GFID) @ UF
  • Merrill low speed wind tunnel @ Caltech
  • NASA Curved Duct Test Rig (CDTR) @ NASA LaRC

• Several areas identified for improvements
  • Underprediction, temperature sensitivity, wire-bonds, EMI and cabling.
Ongoing Work

- Sensors
  - Transition to TSV die
- Packaging Redesign
  - Die endcap – improve flushness, reduce thermal stress
  - Modularity
  - Single cable solution between sensor head and circuit
- Interface Circuit
  - Battery powered instead of wall outlet
- Calibration
  - Sensitivity, FRF, dc drift, environmental characterization, vibration

*Transitioning to pilot production in 2016. Anticipate Q1 2017 commercial availability.*
Acknowledgements

• Work at IC2 funded through NASA SBIRs (LaRC)
  • Phase 1, Phase 2, 2 x Phase 3s
  • Currently wrapping up second P3

• Worldwide exclusive license from UF
  • Patent #US8833175

• LaRC Support
  • Cathy McGinley
  • Luther Jenkins
  • Mike Kegerise
  • Dan Neuhart
Corporate Overview

Mission
To develop and manufacture high-performance, technologically disruptive instrumentation systems that enable the measurement, modeling, and control of various physical properties. Founded in 2001.

Staff
- 5 employees currently, growing to 6-7 within a year

Past Efforts
9 P1s, 2 P2s, 1 P3 SBIR/STTRs (NASA, AF, Army)

Current Efforts
3 Phase 2 SBIR/STTRs
- Highly-Resolved Wall-Shear-Stress Measurement in High Speed Flow (AFOSR)
- Flexible, compact acoustic transducer arrays (Army)
- Miniaturized Dynamic Pressure Sensor Arrays with Sub-Millimeter (mm) Spacing for Cross-Flow Transition Measurements (NASA) – P2 Pending
1 Phase 3 SBIR (NASA)
- Subsonic Wind Tunnel Experiments: Upgraded Skin Friction Sensor Hardware, and Experiment Design.

Capabilities
Miniaturized instrumentation development
- High temperature, miniaturized instrumentation for aerospace applications
- Highly-resolved, high BW acoustic, pressure and shear stress measurement
- Sensors and systems for vehicle and propulsion system design, diagnostics and prognostics
- Optical, capacitive and piezoelectric transducers

Engine Noise reduction
- Acoustic engine liners

Customers/Partners
- University of Florida
- Boeing
- Ducommun
- Boeing
- Foster-Miller
- RTI International
- CRAFT Tech

Company:
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Questions