Sapphire Micromachined Wall Shear Stress Sensors for High-Temperature Skin-Friction Measurements

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• Motivation and Background
• Sensor Development
• Test and Calibration
• Summary
The ability to measure wall shear stress, or skin friction, in high-temperature, high-speed flows is a critical parameter for assessing aerodynamic and propulsion efficiency.

Applications

- Hypersonic transport and missile development
  - Ground test facilities
  - Flight testing
- Compressible flow physics research
  - Transition to turbulence
  - Shock/boundary layer, shock-shock interactions

Historically, indirect sensors such as hot-wires have been used

- Shear stress is inferred from heat transfer measurement
- Restricted to 2D flows
Motivation

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Currently, there is no sensor capable of direct, time-resolved wall shear stress measurement in high-temperature, high-speed flow environments
• **Floating Element Sensors**
  • Integrated shear force causes lateral deflection
  • Tethers act as restoring springs
  • Time-resolved, directional measurement

• **MEMS Sensors**
  • Improved spatial resolution
  • Large bandwidth
  • Reduced cross-axis sensitivity and gap/misalignment effects

• **Transduction Mechanisms**
  • Capacitive
  • Optical
  • Piezoresistive
IC2’s Approach

- Micromachined, floating element optical sensor
  - High-temperature sapphire construction
  - Robust, thermally matched package
  - COTS remote optoelectronics

- Benefits
  - DC measurement capability
  - Minimal thermal drift
  - Immune to EMI
  - Passive & non-conductive
  - High resistance to corrosive & erosive environments
Outline

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

• Components
  • Sapphire shear stress sensor
  • Sensor packaging
  • Optoelectronics
Transduction Mechanism

- Optical transduction method
  - Moiré fringe formation
    - Amplifies sensor displacement
  - Quadrature phase estimation
    - Requires four channel fiber array
    - Minimizes sensitivity to pressure, source drift, and cross-talk

\[
\phi = \frac{2\pi \Delta}{G} = \tan^{-1} \left( \frac{V_{0,3} - V_{0,1}}{V_{0,4} - V_{0,2}} \right)
\]
Sensor Structure

- **Sapphire substrates**
  - Floating element
    - Folded tether design prevents buckling and extends linear range
- **Spacer**
  - Provides controlled gap between floating element and support
- **Backside support**
- **Platinum gratings form moiré fringe**
- **Alumina v-groove fiber array**
Sensor Structure

- Folded tether structure
  - Eliminates buckling due to thermal expansion
  - Extends the linear deflection range over straight tether designs
- Analytical models – quarter sensor
  - Mechanical sensitivity: Euler-Bernoulli beam theory
    \[ S_m = \frac{\delta}{\tau_w} = \frac{W_e L_e L_t^3}{24 EI_y} \left( 1 + 4 \frac{W_t L_t}{W_e L_e} + 2 \frac{W_{tr} L_{tr}}{W_e L_e} \right) \]
  - Resonance: Lumped element model
    \[ f_{res} = \frac{1}{2\pi} \sqrt{\frac{1}{C_{me} M_{me}}} \]
- Design specs
  - Floating element: 2 mm x 2 mm
  - Tether widths: 50 µm
  - Mechanical sensitivity: 2.7 nm/Pa
  - Resonant frequency: 4.4 kHz
Sensor Fabrication

• Process Flow

1) Deposit Cr, pattern PR, over-etch Cr.
2) Deposit Ti and Pt, lift off PR and etch Cr.
3) Laser machine floating element structure.
4) Laser machine support substrate.
5) Laser machine spacer.
6) Align and temporarily bond substrates.
7) Laser machine tapered epoxy wells.
8) Apply ceramic adhesive and laser trim to size.
Sensor Fabrication

- Results – Floating element laser machining
  - Trapezoidal tether section
  - Top width: 42 μm
  - Bottom width: 70 μm
  - 33% decrease in mechanical sensitivity
**Fiber Array Fabrication**

- **Fiber-optic array process flow**
  1. Begin with 10 mm wide bulk alumina substrate.
  2. Laser machine groove array.
  3. Dice substrate into 2 mm wide segments.
  4. Laser machine epoxy wells.
  5. Place fibers into grooves.
  6. Dispense ceramic epoxy.
  7. Align and clamp top cap.

- **Results**
  
  ![Image of MPO connector, Alumina v-groove array, and Sapphire fibers]

  - **MPO connector**
  - **Alumina v-groove array**
  - **Sapphire fibers**
  - **250 μm**
  - **0.5 in**
Sensor Packaging

- Package design
  - Stainless steel housing and flexible fiber conduit
  - Ceramic epoxy used for fiber array and sensor attachment
  - MPO connector allows connection to COTS fiber optics
Optoelectronics

• Provides optical path from LED source to sensor and back to photodiode array

• Photodiode array circuit utilizes transimpedance amplifiers to convert input optical intensities to output voltages
• Motivation and Background
• Sensor Development
• Test and Calibration
  • Calibration
    • Dynamic Shear Stress Sensitivity
    • Pressure Sensitivity
    • DC Stability
  • Wind Tunnel Testing
    • Setup
    • Results
• Summary
• Dynamic sensitivity calibration – plane wave tube
• Dynamic sensitivity calibration – results
  • Test frequency: 1.128 kHz (enable measurement at $\lambda/4$)
  • Shear stress range: 0.7 mPa – 1.9 Pa
  • Poor response in channels 1 and 3 due to location at min/max on fringe
  • Differential (CH4-CH2) sensitivity: 0.17 mV/Pa
• Test frequency: 1.128 kHz
• Dynamic pressure range: 90-160 dBSPL
• Differential (CH4-CH2) pressure sensitivity: 30 nV/Pa
• Pressure rejection ratio

\[ H_p = 20 \log \left( \frac{S}{S_p} \right) = 75 \, dB \]
Characterization – DC Stability

- DC stability test – 20 minute duration
  - Sampling frequency: 100 Hz
  - Differential shear stress variation: +/- 0.5 Pa
  - Nearly 10x reduction from single channel stability measurements
Wind Tunnel Setup

- Supersonic wind tunnel (SWT) – University of Florida
  - Blow-down facility
  - Stagnation pressure: 172 kPa
  - Flow speed: Mach 1.4
  - Cross section: 3” x 4”
Wind Tunnel Results

- Supersonic wind tunnel (SWT) – University of Florida
  - Five test runs: Mach 0.1, 0.2, 1.4 x3
  - Oil buildup on sensor reduced response for later runs
  - Resonance: 4.8 kHz (in-plane), 9.5 kHz (out-of-plane)
Outline

• Motivation and Background
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  • Summary
Summary

• Calibration results
  • Shear stress sensitivity: 0.17 mV/Pa (@1.128 kHz)
  • Resonant Frequency: 4.8 kHz
  • Pressure Rejection Ratio: 75 dB
  • Noise Floor: 0.8 μV/Hz^{1/2}
  • Minimum Detectable Shear Stress: 4.7 mPa
  • Dynamic Range: > 52 dB (limited by test setup)
  • DC Stability: +/- 0.5 Pa

• Sensor demonstrated in Mach 1.4 wind tunnel
  • Mean and fluctuating shear stress data captured
  • Demonstrated survivability at higher flow speeds and shear stress levels

• Several areas identified for improvements
  • DC stability, bandwidth, sensor robustness, optoelectronics
Ongoing Work

• Sensors
  • Refinements to laser machining processes
  • Creation of optimized sensor designs based on application requirements and fabrication constraints

• Packaging Redesign
  • Improve attachment of fiber array to sensor
  • Reduce losses in sapphire fiber array
  • Stepped housing

• Optoelectronics
  • New photodiode array circuitry for improved stability and bandwidth
  • Implement differential amplifiers
  • Custom enclosure for fiber optics and electronics

• Calibration
  • Determine thermal drift of the system
  • Implement high-temperature shear stress calibration system
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• Work at IC2 funded through AFOSR STTRs
  • 2x Phase 1s, 2x Phase 2s
  • Second Phase 2 commenced 4/1/2016

• Publications
**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**

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Questions