Unsteady Heat-Flux Measurements of Second-Mode Instability Waves

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Introduction

• Atomic Layer Thermopile (ALTP) sensors
  – Provides a time-resolved heat-flux measurement
  – Good spatial resolution: ~1 mm
  – Frequency response on the order of 1 MHz
  – Linear static response over several orders of magnitude (from mW/cm\(^2\) to kW/cm\(^2\))

• Well suited for measurements of unsteady heat transfer in a wide range of flow problems
  – Heat transfer in turbomachinery
  – Stagnation point heating
  – Shock-boundary layer interactions
  – Measurements in short duration supersonic and hypersonic facilities
  – Laminar-to-turbulent transition
Objectives

• Gain experience with the ALTP sensors for measurements in transitional hypersonic boundary layers
  – Previous work by Roediger et al (2009), Roediger (2010), and Heitmann et al (2010) demonstrated this application in short-duration hypersonic wind tunnels
  – Demonstrate application in our conventional hypersonic blow-down tunnels

• Develop the capability to dynamically calibrate the ALTP sensors
  – Measurements of the sensor frequency response function
  – Critical for cross-correlations and cross-spectral analysis with multiple sensors

• Measure second-mode instability waves on a flat plate model in a Mach 6 freestream flow
Atomic Layer Thermopile (ALTP) Sensors

- Sensor area of 1 mm$^2$
- Nominal bandwidth of ~1 MHz
- Nominal static sensitivity of 48.0 µV/W/cm$^2$
- Signal from ALTP sensor is amplified with a miniature amplifier placed inside the model
  - AC coupled signal has a fixed gain of 5000 and bandwidth from 17 Hz to 1 MHz
  - DC coupled signal has adjustable gain from 100 to 800 and a bandwidth of 100 kHz
Experimental Setup for Dynamic Calibration of the ALTP Sensors

- **Laser Diode Driver & Temp Control**
- **Function Generator**
- **Temperature controlled laser diode mount** (500 mW, 670 nm laser diode)
- **Collimating Optics** $f = 8$ mm aspheric lens
- **Anamorphic prism** with 3.0 Mag.
- **Elliptic beam** approximately 1.0 mm by 3.0 mm
- **Shutter connected to laser interlock**
- **Beam splitter** 90R:10T
- **Adjustable Iris**
- **90R**
- **10T**
- **Photo-diode detector** (reference beam)
- **ALTP Sensor**

*~3 mm diameter beam*
Frequency Response Measurement Details

- Amplitude modulate radiant heat-flux input with a sine wave
- Collect time-series data for a range of sine-wave frequencies
- Calculate the frequency-response function between the reference input measured by the photo diode and the output of the ALTP sensor amplifier

\[
H(f) = \frac{G_{xy}(f)}{G_{xx}(f)}
\]

\[
\begin{align*}
|H(f)| & \quad \text{Magnitude} \\
\angle H(f) & \quad \text{Relative Phase}
\end{align*}
\]

Acquisition and Processing Parameters

- \(F_s = 2\) MHz
- \(N_{samp} = 4 \times 10^6\)
- \(N_{fft} = 50000\)  \(N_{blk} = 160\)
- Hanning Window, 50% overlap
- \(\Delta f = 40\) Hz
Sample Time Series Data for Dynamic Calibration

Red Curve: Reference Photodiode
Blue Curve: ALTP Sensor

1743 Hz
78.8 kHz
Frequency Response of ALTP Sensors

$|H(f)|$ (dB re 1)

$\angle H(f)$ ($^\circ$)

Black Symbols: Pre-Test Measurements
Blue Symbols: Post-Test Measurements

$f_{-3dB} = 650 \pm 25$ kHz

$\phi_{-3dB} = -92.9^\circ \pm 3.1^\circ$
Experimental Setup

• Facility
  – Langley Aerothermodynamics Laboratory
    20-Inch Mach 6 Tunnel
  – Conventional blow-down tunnel
  – Test Gas: Air
  – Re Range: 1.6 to 28.5x10^6/m
  – Total Temperature: 465 to 520 K

• Flat plate model
  – 71.12 cm long by 27.94 cm wide
  – Sharp leading edge
  – AOA of zero and -5 degrees
  – ALTP sensors were mounted in a streamwise array along model centerline
  – 16 sensor locations were available from x = 21 cm to 63 cm with 2.8 cm spacing
  – For a given run, 4 ALTP sensors were installed
Heat Flux Power Spectral Densities

Heat Flux Power Spectral Densities at $x = 26.54$ cm for a range of freestream unit Reynolds numbers and an AOA of zero degrees

Streamwise evolution of heat flux power spectral density at a unit Reynolds number of 5 million/m and an AOA of zero degrees
Sample Heat Flux Time Series

- Heat flux time series at several streamwise positions acquired simultaneously during a run
- Time series were band-pass filtered about the most unstable second mode frequency (70 to 200 kHz)
- Unit Reynolds number of 8 million/m
Second-Mode Wave Parameters

Measured phase speed for the most unstable second-mode disturbances

\[ \frac{c_p}{u_c} \times 10^{-6}/m \]

- 3.5
- 5.0
- 6.8
- 8.1
- 9.7
- 13.3
- 16.6

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Measured wavelength for the most unstable second-mode disturbances

\[ \frac{\lambda}{\delta} \times 10^{-6}/m \]

Note: The boundary layer thickness, \( \delta \), was based on the laminar similarity solution with a Sutherland viscosity model.
Run-to-Run and Sensor-to-Sensor Repeatability

Heat flux power spectral densities measured with different sensors at \( x = 29.34 \) cm and a unit Reynolds number of 5 million/m.

Heat flux power spectral densities measured with the same sensor in two different runs at \( x = 40.51 \) cm and a unit Reynolds number of 5 million/m.

Issues with static calibration? Accuracy of static sensitivity? How flush is sensor plug with model surface?
Summary

• Dynamic calibration via laser-based radiative heating
  – Frequency response of our ALTP sensors was 650 kHz
  – Sensor-to-sensor frequency response functions were nearly the same
  – Pre- and post-test measurements of frequency response functions were essentially the same

• Measurements of second-mode instability waves on a flat plate model in a Mach 6 freestream
  – Results are in-line with what we expect from theory and previous measurements
  – Most-amplified second-mode frequency varies inversely with boundary-layer thickness
  – Phase speed is roughly 90% of the freestream velocity
  – Instability wavelength is roughly twice the boundary-layer thickness

• ALTP sensor measurement repeatability
  – Run-to-run repeatability for a given sensor is acceptable
  – Sensor-to-sensor measurements at a given port location show some variability
  – How accurate is the static calibration?
  – How stable is the static calibration over time?
  – How flush is the sensor with the model surface?
Backup Slides
Heat-Flux Statistics

Mean Heat Flux

\[ Q \text{ (W/cm}^2) \]
\[ Re \times 10^{-6}/m \]
- 3.5
- 5.0
- 6.8
- 8.1
- 9.7
- 13.3
- 16.6

Broadband R.M.S. Heat Flux

\[ \langle q^2 \rangle^{1/2} \text{ (W/cm}^2) \]
\[ Re \times 10^{-6}/m \]
- 3.5
- 5.0
- 6.8
- 8.1
- 9.7
- 13.3
- 16.6