Hypersonic Flow Diagnostic of Boundary Layer Transition Length in a PSWT

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Abstract

This research investigates the transition from laminar to turbulent boundary layers in hypersonic flow, a critical phenomenon impacting high-speed vehicles' aerodynamic and thermal performance. Previous studies have established that second-mode instabilities—high-frequency acoustic waves—play a dominant role in destabilizing boundary layers under hypersonic conditions. The growth of these acoustic waves depends on the acoustic environment, resulting in varying transition lengths among wind tunnels. To characterize the acoustic environment of FAMU-FSU's PolySonic Wind Tunnel (PSWT), amplification rates of these perturbations will be measured and compared with those in other facilities.

A seven-degree half-angle cone at zero angle-of-attack, designed using SolidWorks, will be tested in the PolySonic wind tunnel. The study intends to characterize the transition onset using pressure sensors and Schlieren imaging data. Signal analysis using Fourier transforms in Python will focus on identifying dominant frequencies associated with boundary layer perturbations.

By measuring the amplitude growth of second-mode instabilities and mapping transition lengths, this research seeks to validate theoretical models and characterize the acoustic environment within the specific conditions of the AME wind tunnel. The results are expected to enable boundary layer transition experiments to be performed with a measurable baseline. Transition studies aim to enhance understanding of hypersonic boundary layer dynamics and provide critical data for improving computational models. This work aims to inform the design of hypersonic vehicles by aiding in the prediction of transition points, thereby minimizing boundary layer-induced drag and thermal loads. Future extensions of the research will consider varied geometries and flow conditions to generalize findings.

Introduction & Background

Part 1: Existing Facts

- Hypersonic flight occurs at flow velocities exceeding five times the speed of sound (M>5)
- Boundary layer transition from laminar (smooth, stable) to turbulent (chaotic) flow is critical for high-speed vehicle performance.
- This transition results in Increased heat transfer, Higher drag and skin friction, Greater overall flow instability

Factors affecting the transition include **Reynolds** number, **Mach** number**, angle of attack**, and surface conditions.

- Second-mode instabilities, characterized by high-frequency acoustic waves, are a key driver of transition under hypersonic conditions.

Part 2: Shortcomings

- Research Gap: Experimental studies have confirmed second-mode instabilities in many environments but not specifically in the AME polysonic wind tunnel (PSWT).
- The unique flow conditions of this facility, including pressure, temperature, and turbulence characteristics, require experimental validation.
- Why This Matters: Without localized data, models for hypersonic systems lack validation, limiting their accuracy for vehicle design.

Part 3: Purpose and Hypothesis

- Purpose: This research aims to confirm second-mode instabilities in the AME wind tunnel using a seven-degree half-angle cone.
- Hypothesis: Second-mode instabilities will manifest as predicted by theoretical models, with measurable effects on transition onset and transition length.

Acknowledgments

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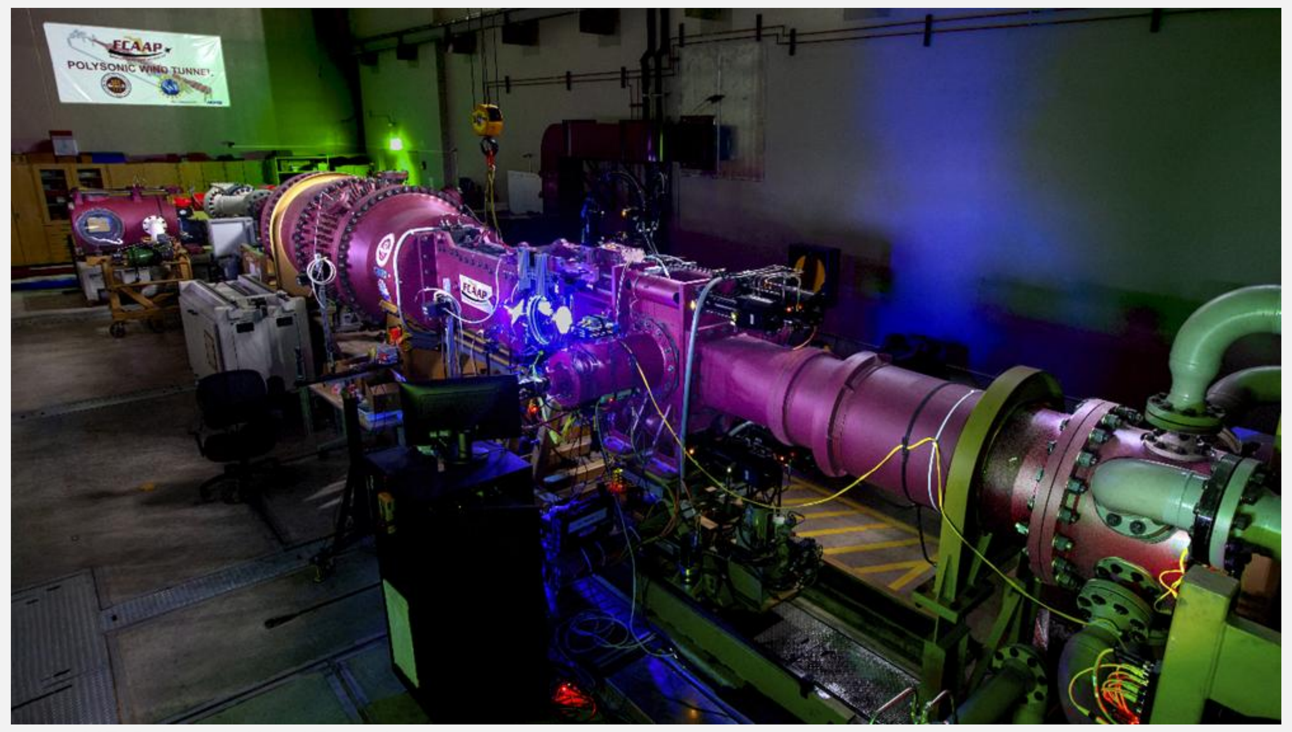
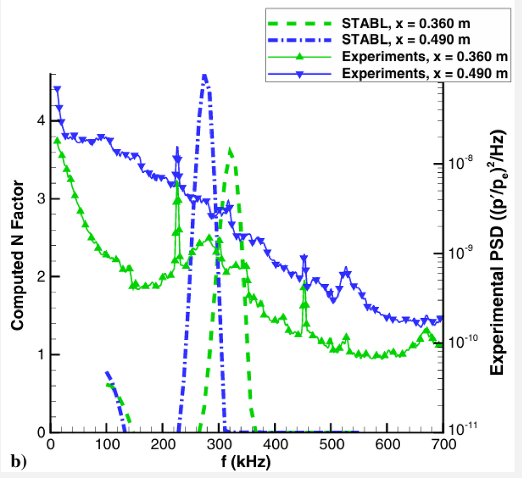
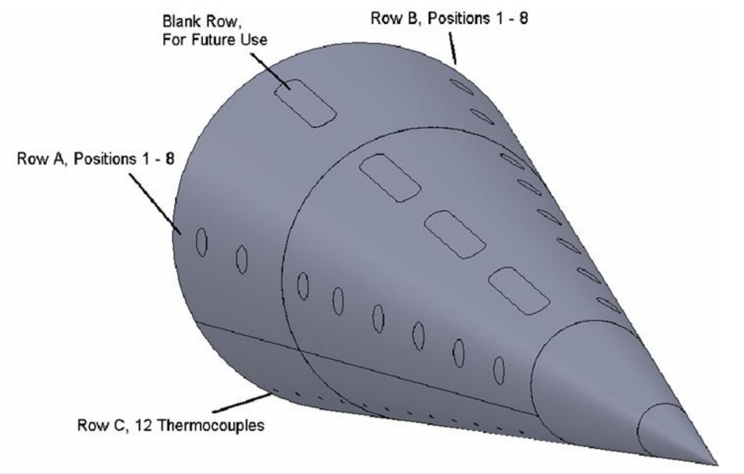


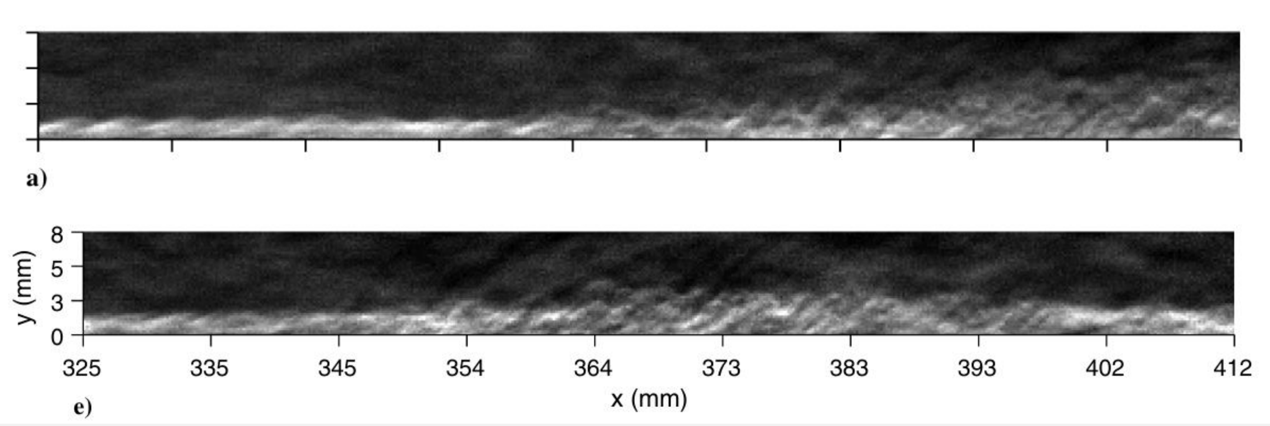
AME. Polysonic Wind Tunnel



N-Factor Graphs (casper et al. 2016)



7-Degree half-angle cone 3D design



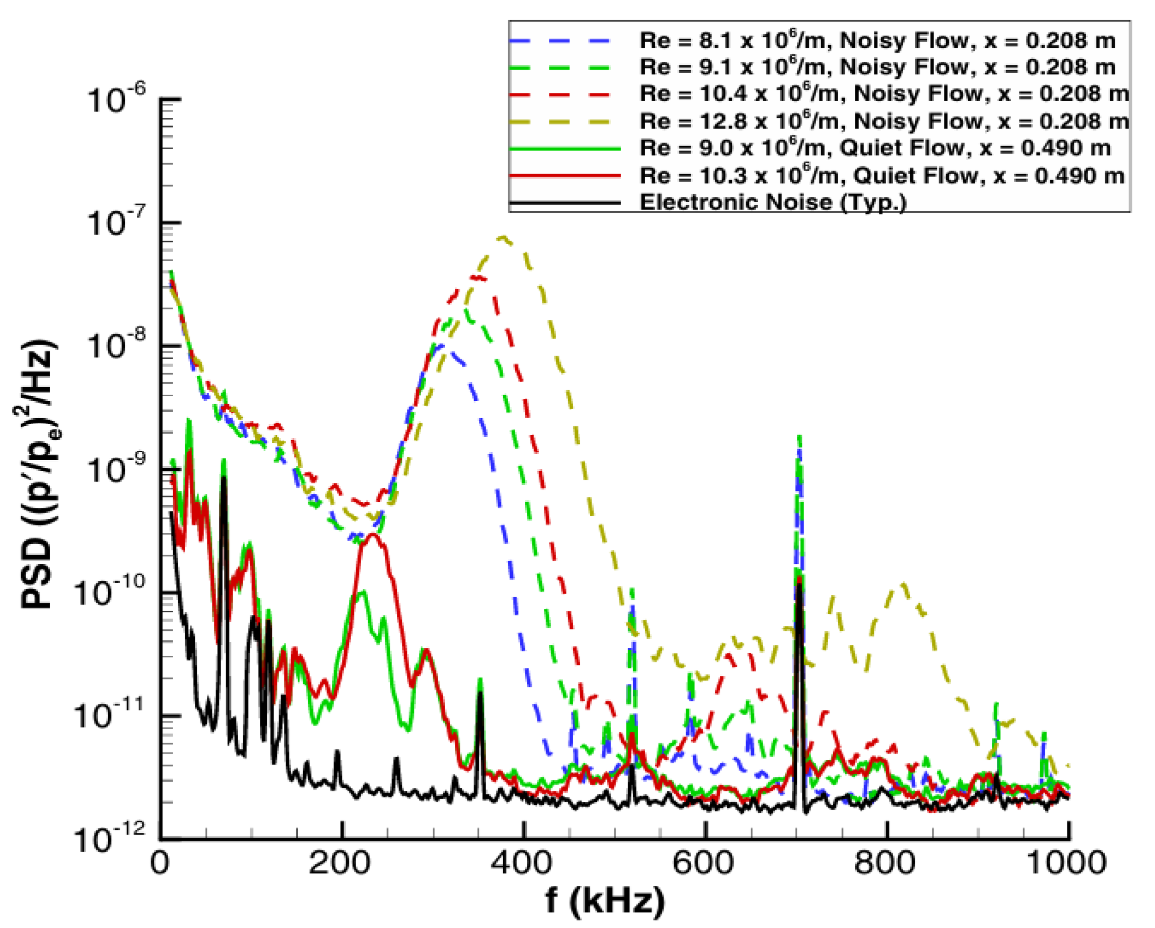


Fig. 14 PCB132 PSDs showing second-mode waves under noisy and quiet flow, BAM6QT.

PSD signal graph and Schlieren Imaging (Casper et al. 2016)

Methods

Part 1: Participants

- **Subject of Study:**
  - A seven-degree half-angle cone designed using SolidWorks will be the primary test subject.
  - The study focuses on characterizing second-mode instabilities in the boundary layer transition using this geometry.

Part 2: Materials and Measures

- **Wind Tunnel Setup:**
  - AME polysonic wind tunnel capable of simulating hypersonic flow conditions
- **Instruments and Measurements:**
  - **Pressure Sensors:** An array of sensors distributed along the cone's surface to measure pressure fluctuations and instability growth.
  - **Schlieren Imaging System:** Visualization of density gradients within the boundary layer to identify disturbances.
  - **Data Logging Systems:** Systems for continuously recording pressure data during tests.

Part 3: Procedures

1. **Model Preparation:** The seven-degree cone model will be fabricated and mounted at zero angle of attack in the wind tunnel.
2. **Wind Tunnel Test:**
   - The test will simulate hypersonic flow conditions matching specific Mach and Reynolds numbers.
   - Initial test runs will ensure sensor calibration and Schlieren imaging alignment.
3. **Data Collection:**
   - Pressure sensors will log high-frequency signals related to boundary layer disturbances.
   - Schlieren imaging will capture visual evidence of instability growth and transition onset.

Part 4: Data Analysis *(Planned)*

- **Signal Processing Tools:**
  - Data from pressure sensors will be processed using **Fourier transforms** in Python to detect dominant frequencies associated with second-mode instabilities.
  - Spectral Analysis: Pressure spectral density analysis will be used to highlight regions of instability.
- **Visualization of Disturbances:**
  - Schlieren imaging will be analyzed to correlate visual disturbances with pressure sensor data.

Findings and Results

It is anticipated that:

- **Pressure spectral analysis** will reveal dominant instability frequencies consistent with second-mode instabilities.
- **Schlieren imaging** will visually capture disturbances in the boundary layer, supporting the presence of instability growth leading to transition.
- **Transition onset locations** will be determined by correlating pressure sensor data with known instability behavior, providing insight into the boundary layer's response to hypersonic flow conditions.

This research seeks to address two primary questions:

1. *Can second-mode instabilities be experimentally confirmed in the AME PolySonic wind tunnel?*
2. *How do the observed transition lengths and instability frequencies compare to theoretical predictions?*

Second-mode instabilities have been widely studied in hypersonic aerodynamics, but experimental validation within the AME wind tunnel remains incomplete. By conducting controlled tests, this study will provide data to bridge this gap and support the refinement of computational models for predicting hypersonic boundary layer behavior.

<u>Significance of Results</u>

- Provide **direct experimental validation** of second-mode instabilities under controlled conditions.
- Improve **computational fluid dynamics (CFD) models** by providing high-fidelity experimental data.
- Enhance the design of **hypersonic thermal protection systems**, which rely on accurate transition onset predictions.
- Contribute to the broader aerospace field by offering insights critical for the **development of future hypersonic vehicles**.

<u>Ongoing</u>

This research is ongoing.
Future work will explore:

- **Different cone geometries** to assess the impact of shape on transition onset.
- **Various Mach and Reynolds number conditions** to generalize findings.
- **Additional diagnostic tools**, such as infrared thermography, to measure heat transfer effects during transition.

Resources

Casper, K. M., Beresh, S. J., Henfling, J. F., Spillers, R. W., Pruett, B. O. M., & Schneider, S. P. (2016). *Hypersonic wind-tunnel measurements of boundary-layer transition on a slender cone*. **AIAA Journal, 54**(4), 1250–1263