Possible Secondary Instability of Stationary Crossflow Vortices on an Inclined Cone at Mach 6

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AIAA Paper 2015-2773
Presented at the 45th AIAA Fluid Dynamics Conference
Dallas, Texas
23 June 2015

Plus some of Joshua Edelman’s data, not yet published
Hypersonic Boundary-Layer Transition

- Boundary-layer transition is a complicated and poorly understood process.
- State of boundary layer affects heat transfer, skin friction and separation.
- Prediction of transition is inexact, and can dramatically affect the design of flight vehicles (especially hypersonic vehicles).
- Empirical and semi-empirical methods are used to predict transition.
- Better understanding of the flow physics that causes transition will aid development of better methods.

13-foot Beryllium Cone at Mach 20 in Reentry CFD predicts heating well --ONLY IF-- transition location picked to match flight

Transition Uncertainty 300%
Laminar Uncertainty 15%
Turbulent Uncertainty 20%

Freestream Disturbances in Hypersonic Tunnels

- Nozzle-wall turbulent boundary layer radiates high levels of noise (acoustic fluctuations)
- Conventional tunnels have noise levels an order of magnitude larger than quiet tunnels with laminar nozzle-wall boundary layers
- Tunnel noise moves transition upstream and can change the mechanism and the parametric trends.

Shadowgraph of 5 degree sharp cone at M=4.31, $\alpha = 0$, $Re = 31.9\times10^6$/foot, Naval Ordnance Lab Ballistics Range
Crossflow Instability

- Inflection point in crossflow velocity is a source of an inviscid instability.
- Primary instability shows up as co-rotating vortices in the boundary layer.
- The crossflow vortices can be travelling or stationary with respect to the surface.
- Low speed experiments show that the travelling vortices dominate transition in high-disturbance environments, while stationary vortices dominate transition in low-disturbance environments.

Secondary Instability of the Stationary Vortices

Does this occur at High Speed also? In this paper, more preliminary evidence from the Mach-6 quiet tunnel.

15° half angle cone at 0° AoA rotating in an air stream of 2.9 m/s

- When stationary vortices saturate, secondary instabilities appear, at least at low speeds.
- Secondary instabilities travel along the stationary vortices at frequencies higher than the primary travelling instability.
- These secondary instabilities are believed to cause break down of the stationary vortices to turbulence. See Malik and many others
- Crossflow-induced transition occurs along a jagged transition front.

Image from “An Album of Fluid Motion”, Van Dyke, Parabolic Press, 1982.
• Sharp 7-deg half-angle cone, 3-6° angle of attack.
• Test under quiet flow with either smooth or rough insert.
• Roughness elements 0.05 m from the nosetip, near the neutral point of the most amplified stationary waves (Li et al. AIAA Paper 2010-4643)
• 50 roughness elements placed around the azimuth.
• Crater roughness element has an approximate depth of 30 μm, diameter of 300 μm and a height of 10 μm (after Corke and Schuele).
Possible Secondary Instability, Case 1

• 4° AoA, Re = 12.01e6/m
  • Top: Smooth surface
  • Bottom: Nail-polish ring

• PCB shows a disturbance near 475 kHz, only in rough case where crossflow streak is visible near sensor
Possible Secondary Instability, Case 2

- Vortex streak crosses Kulite at the 94.5° ray. A large disturbance is observed at 410 kHz.
- Kulite at the 92.25° ray shows a smaller disturbance at the same frequency.
Reynolds number effects on apparent secondary instability

- 3° AoA
- \( \text{Re} = 10.40-9.84 \text{e}^6 / \text{m} \)

- During a single run, Reynolds number will decrease as the expansion fan in the driver tube reflects between the upstream end and the contraction.

- As \( \text{Re} \) decreases, stationary-wave amplitudes also decrease, as seen by a decrease in heat transfer in the TSP images.
Reynolds number effects on apparent secondary instability

- 3° AoA
- Re = 10.40-9.84e6/m

- A disturbance near 260 kHz is found. The PCB frequency decreases with Reynolds number, along with the mean heat flux from the TSP.

- From heat flux profiles, vortex that crosses over the sensor is on its initial growth region, not in a saturation region, unlike at low speeds. How does all this really work, at hypersonic speeds?
Effect of Azimuthal Angle on Possible Secondary Instability

- The frequency consistently decreases when the instability is found closer to the lee ray.

- The boundary layer on the cone is thicker towards the lee ray (180-deg).

- The frequency of the secondary instability appears to be a function of boundary-layer thickness, as might be expected.

Here, 10 cases where apparent secondary instability was found.
High-Frequency Instability Appears When Stationary Modes Grow Large (TSP data)

6-deg AoA, Lee side, quiet flow, Re – 9.3x10^6 /m

- Kulite sensor among 4 circled in the images (150° ray).
- When the roughness is added, several stationary vortices grow large near the Kulite array, and may be breaking down to turbulence.
High-Frequency Instability Appears When Stationary Modes Grow Large (PCB data)

- Amplitude of stationary vortex near the sensor array shows saturation near the sensor location.
- The spectra show the primary travelling instability is visible near 40 kHz.
- When the stationary wave grows large and possibly begins to break down to turbulence, a secondary peak at 150 kHz appears in the PSD.
- Is this 150 kHz peak due to a secondary instability?
Instability Sensitive to Small Changes in Azimuthal Angle

- 6-deg AoA, Re – 10.8 x 10^6 /m, roughness insert installed (no TSP available).
- PCB sensor 120-deg from windward ray shows large peak at 400 kHz.
  - Evidence of the secondary instability?
- Peak disappears when sensors rotated several degrees.
- Second peak visible near 200 kHz.
  - Also related to the secondary instability?
Peak Amplitude and Frequency Decrease with Decreasing Reynolds Number

- Data from a PCB sensor 0.36 m from the nosetip on the 120° ray at different times during a single run.
- As the Reynolds number decreases, the amplitude and the frequency of the peak decreases.
- This could be caused by the movement of the transition location or the thickening of the boundary layer with decreasing Reynolds number.
Another Possible Secondary Instability on Stationary Crossflow Wave

Data included for PCBs 1 and 5, shown above with streak passing through.

Modified Cone with Two azimuthal arrays of PCB-132 sensors

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Run Table

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- PCB 1.5 at 132° from windward ray
- 6° AoA
- Roughness insert, 50 dimples, 0.004” depth
Spectra: PCBs 1 (Upstream) and 5 (Downstream)

Secondary Instability Near 250kHz?
Decreases with Re

Travelling crossflow wave

PSDs from Welch’s method, frequency resolution of 2 kHz. PCB 5 is downstream of PCB 1.

Normalized by edge pressure for cone at zero angle of attack (Taylor-Maccoll).
High Value of the Magnitude Squared Coherence for PCBs 1 & 5 (when not turb.)

![Graph showing coherence for PCBs 1 & 5 across different Re values.]

- Travelling crossflow wave
- Potential secondary instability

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Summary

• A high frequency instability was frequently measured near the break down of stationary crossflow waves, with a frequency between 150 and 500 kHz.

• The frequency of the disturbance appeared to decrease with increasing azimuthal angle and increasing boundary layer thickness (as expected).

• The instability was sensitive to small changes in azimuthal angle.

• The instability was also sensitive to the amplitude of the stationary wave.

• Based on the experiments, it appears that the instability is the secondary instability of the stationary crossflow.

• However, we seek computational comparisons

• Further measurements will be part of Edelman’s MS thesis