ONR Hypersonic Transition and Turbulence (HTT) Project: Y1 review

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AFOSR/ONR/HVSI Hypersonic Aerothermodynamics Portfolios Review
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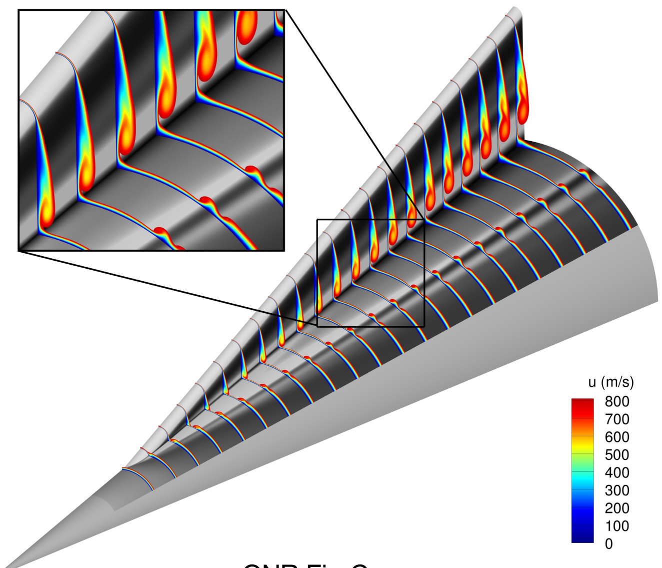
Aerothermal Prediction Challenges for Complex Geometries

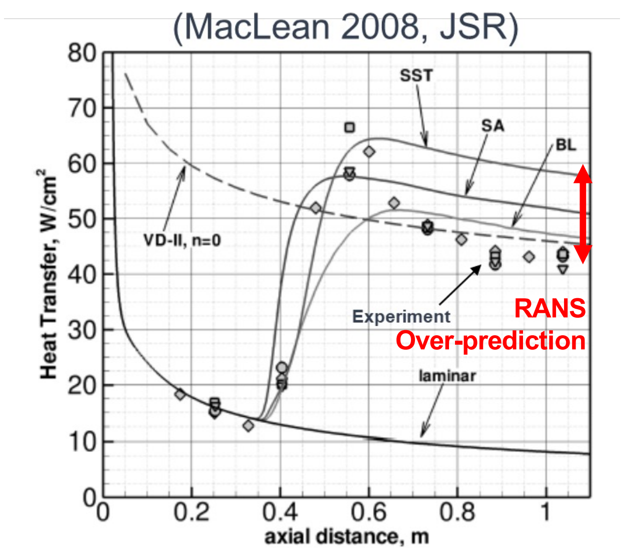
Accurate modeling of boundary layer flow (laminar, transitional, turbulent) is important to balance **robust design** (heating, drag, control, sensing) with **optimal performance** (speed, range, maneuverability) of hypersonic vehicles.

Challenge #1: **Legacy boundary layer transition prediction tools are often too simplistic** for complex vehicle shapes with highly three-dimensional flow fields.



ONR Fin-Cone

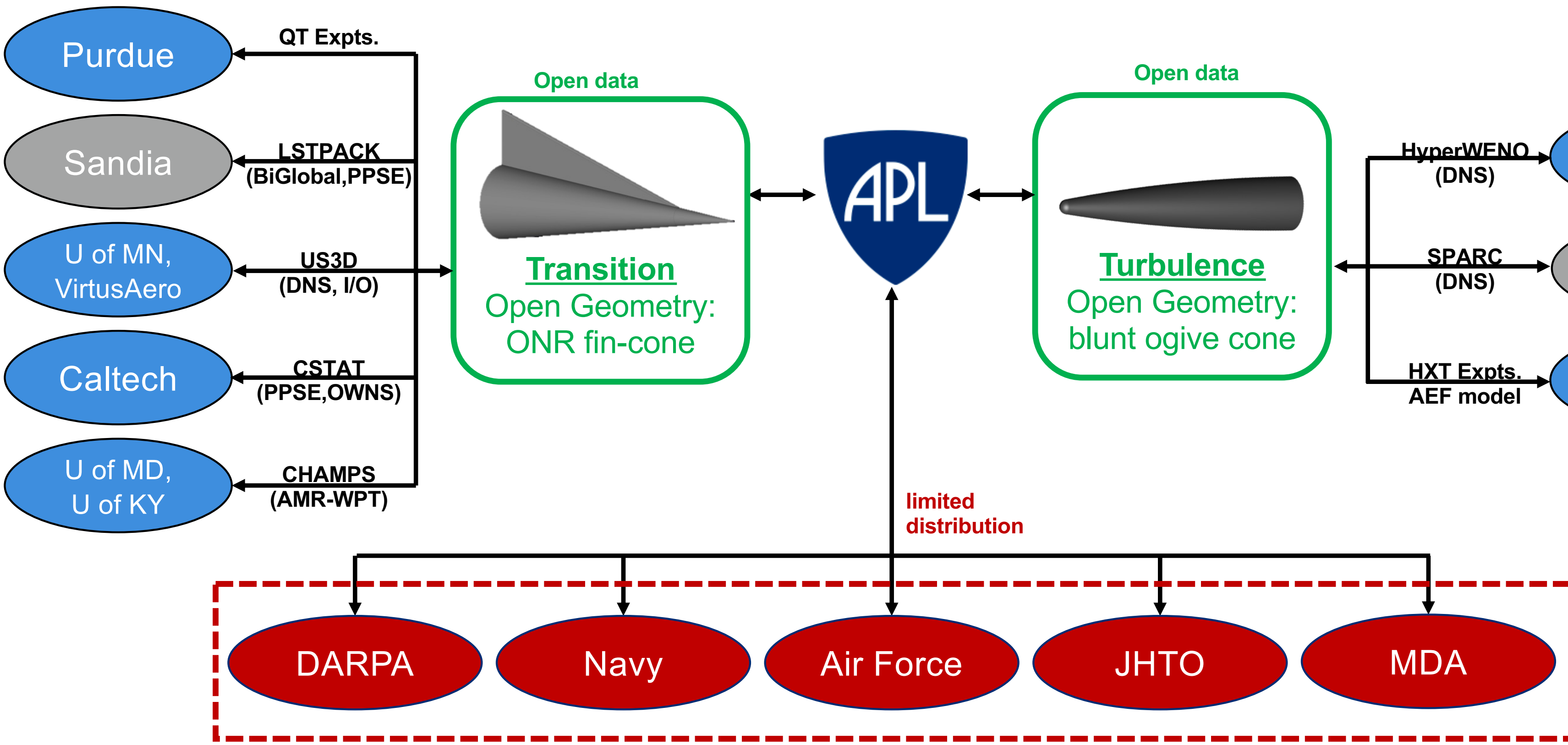
Challenge #2: Wind tunnel tests frequently show that **RANS models over-predict turbulent heating by as much as 2X** at flight-like conditions.



HIFiRE-1

Project Overview

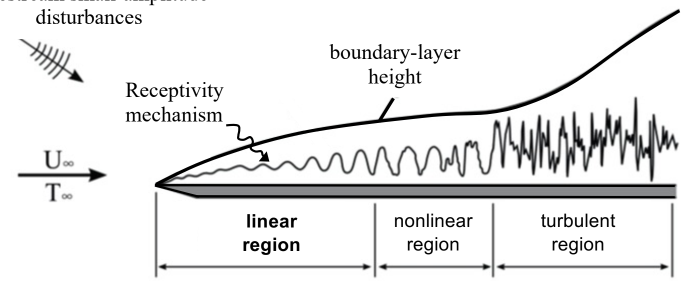
HTT is a 3-year project that seeks to bridge the gap between fundamental research and hypersonic vehicle development by applying cutting-edge modeling tools to multiple DoD relevant geometries.



Part 1: Linear Analysis of Hypersonic Boundary Layer Transition

Approach:

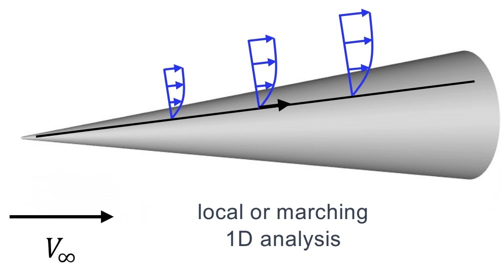
- Utilize *linear* stability methods to predict transition onset for select complex geometries (open & limited distribution).
- Compare transition onset predictions with experimental measurements.
- Assess the pros, cons and relative robustness of each method and report the findings with recommendations for future use.



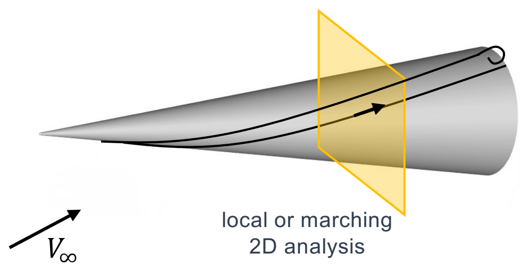
Sketch adapted from D. Masutti (2013) as described in E. Roshotko (2008)

Basic assumptions of linear stability methods:

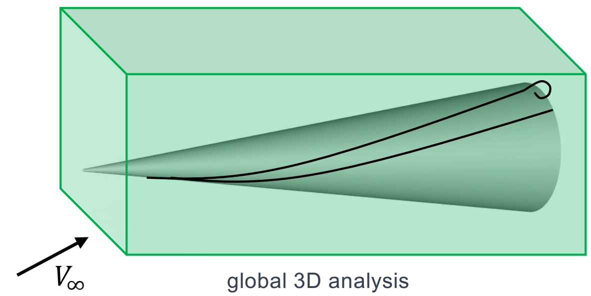
LST, **PSE** governing equations assume mean flow with strong variation in 1D



BiGlobal, **Planar PSE**, **OWNS** governing equations assume mean flow with strong variation in 2D



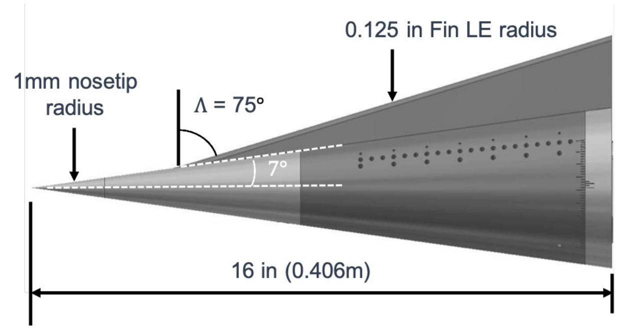
I/O, **forced-DNS**, **AMR-WPT** governing equations assume arbitrary mean flow variation



Araya, D., Bitter, N., Wheaton, B.M., Kamal, O., Colonius, T., Knutson, A., Johnson, H., Nichols, J., Candler, G.V., Russo, V. and Brehm, C., (2022). "*Assessment of Linear Methods for Analysis of Boundary Layer Instabilities on a Finned Cone at Mach 6*". In *AIAA AVIATION 2022 Forum*. **(AIAA 2022-3247)**

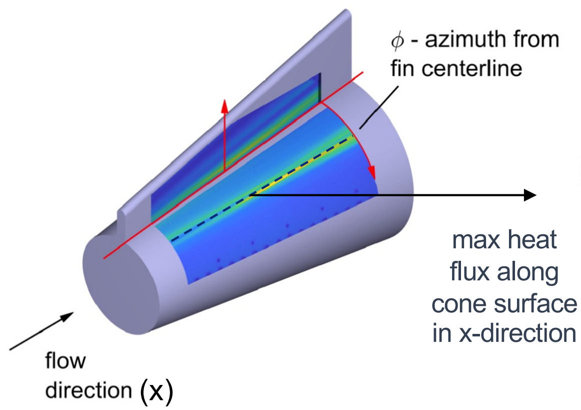
Experimental conditions for linear methods case study

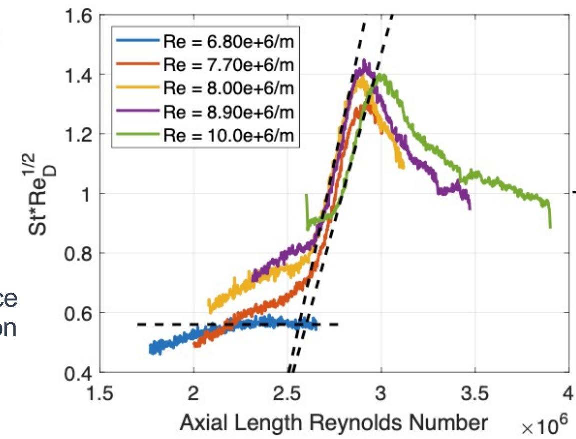
- **BAM6QT finned-cone model [1] used for case study:**
  - 7° cone with 1mm nose and 75° swept fin
  - PEEK frustrum (and fin) for IR surface heat flux measurements
  - PCB sensors on rotatable frustum to measure pressure fluctuations.



- **Mach = 6, Re=8.4e6/m freestream conditions selected for stability analysis based on latest experimental data:**

[1] Turbeville, F. D., and Schneider, S. P., "Effect of Nose Bluntness on Fin-Cone Transition at Mach 6," AIAA Aviation Forum, 2021.



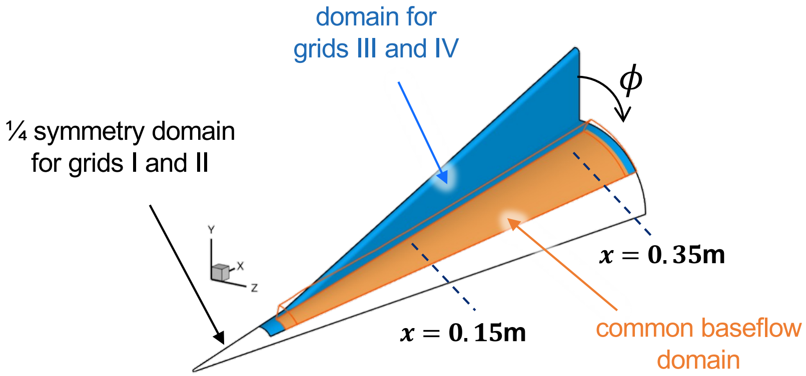


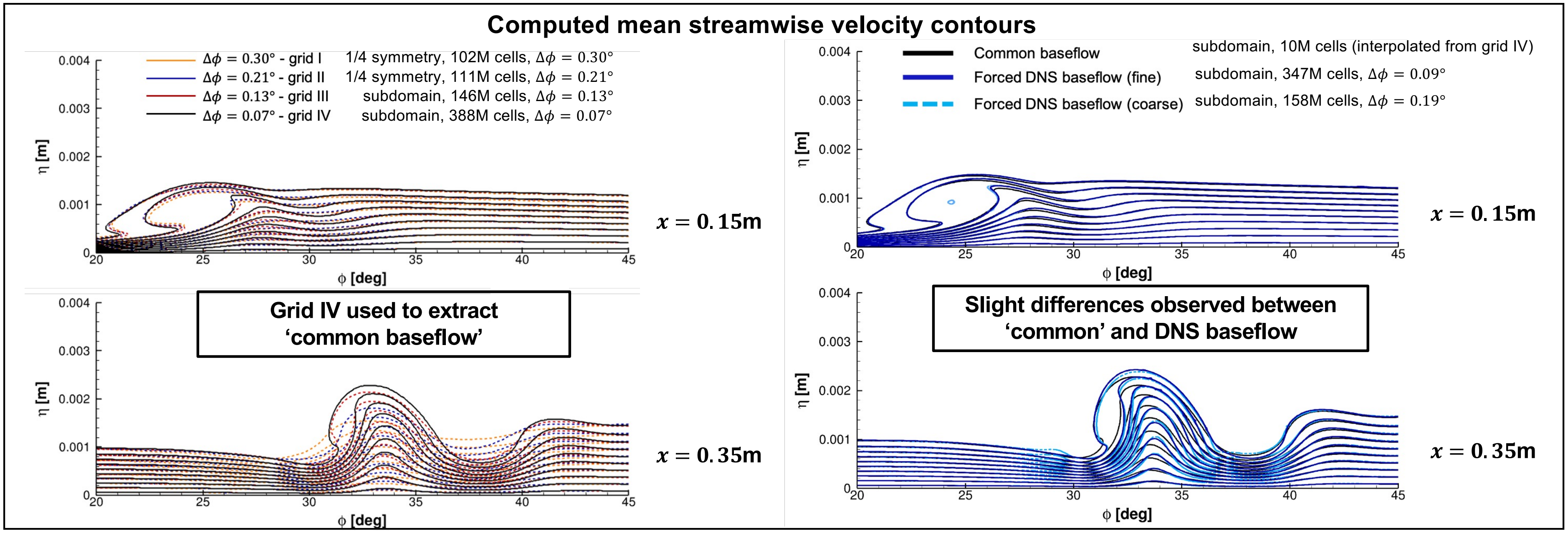
Transition estimate for finned cone with 1mm radius nosetip: $\boldsymbol{Re_{x,tr}}$ **~2.56e6**

$\boldsymbol{X_{tr}}$ **~ 0.31 m (**for Re=8.4e6/m)

Laminar baseflow computation

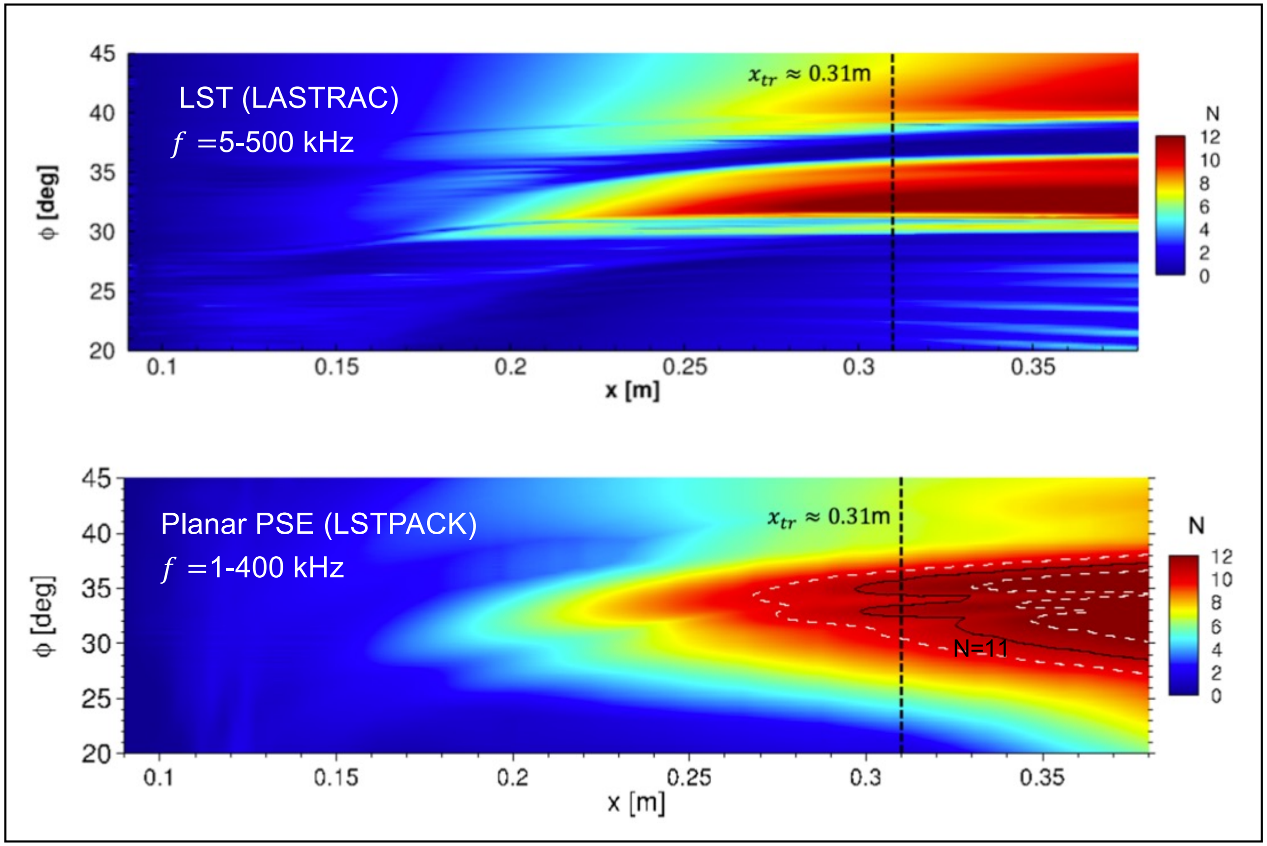
- **Baseflow grids**
  - Link3D software used to generate all (hexagonal) grids.
  - 4 grids (I-IV) created initially with increasing azimuthal resolution.
  - Grids I & II assumed quarter symmetry
  - Grids III & IV subdomain grids
  - Forced DNS required independent baseflow grid
- **Baseflow solver:** US3D CFD software
  - 'common' baseflow computed with 2nd order spatial fluxes and Mach dissipation switch.
  - Forced DNS baseflow computed with 4th order spatial fluxes and dilatation-based switch.

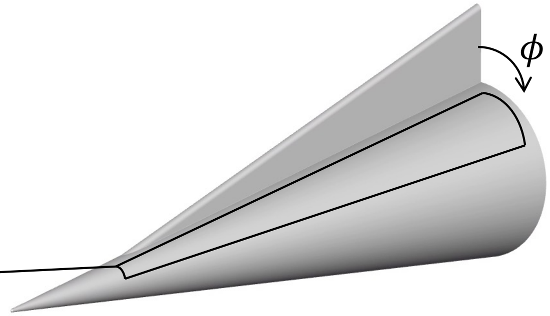




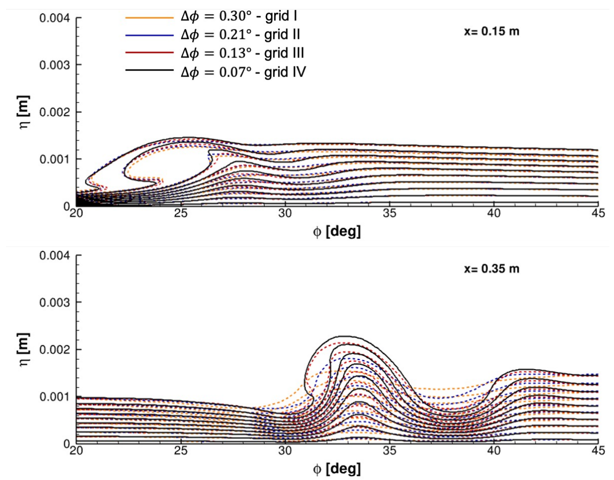
Initial surface N-factor predictions

- What boundary layer instability most likely leads to transition?



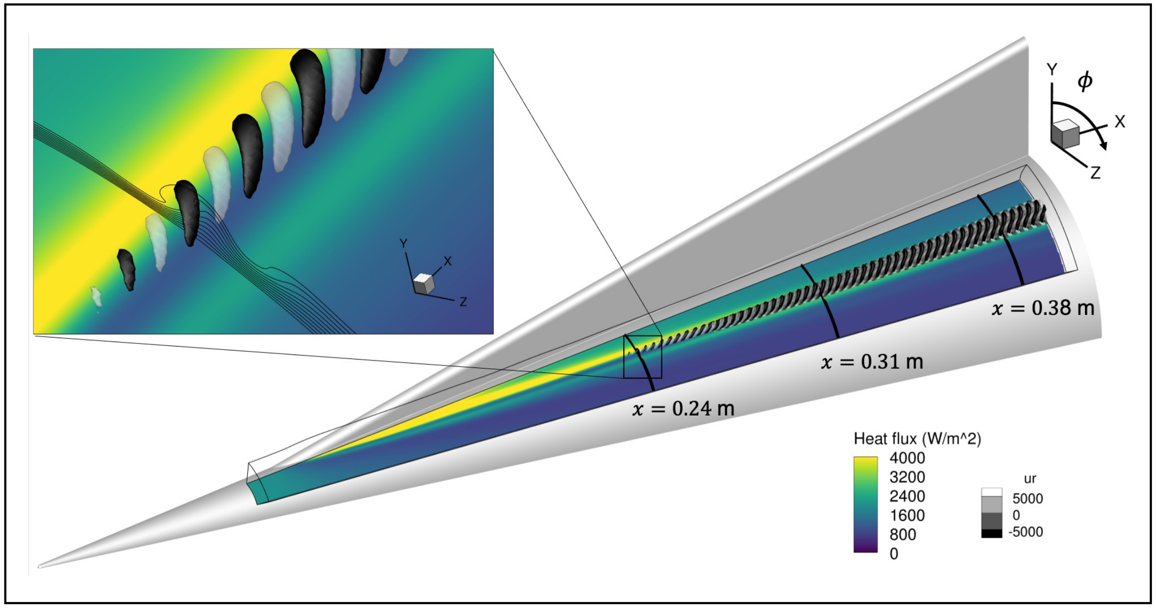


- **Largest N-factor appears within $\phi = 30 - 35°$ for both LST and planar PSE (at similar frequencies)**
- **LST misses growth in some regions and parallel flow approximation is suspect near large vortex.**

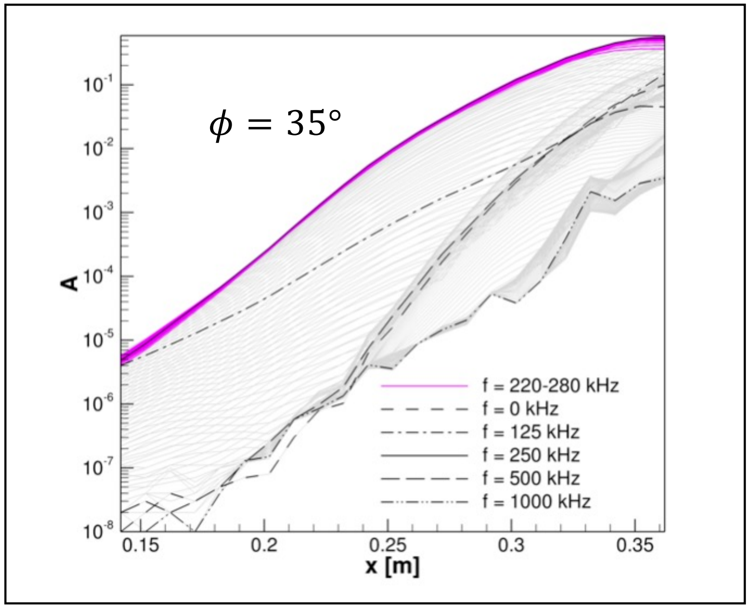


Most unstable mode

- Planar PSE analysis used to identify most unstable mode at ~250kHz that appears above laminar vortex closest to the fin.
  - Visualization of vortex mode shown with iso-surfaces of streamwise velocity fluctuations shown (below left).
- AMR-WPT predictions consistent with planar PSE showing largest amplification at ~250kHz.
  - Disturbance amplification of various frequencies along fixed azimuth shown (below right).

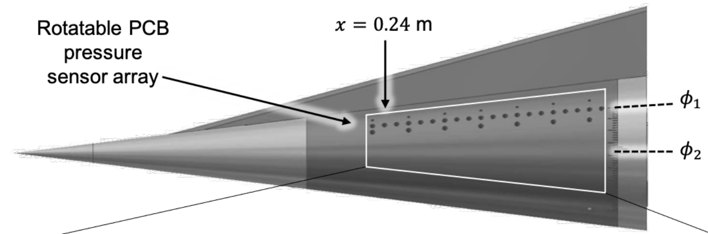


Planar PSE prediction for most unstable mode at 250kHz



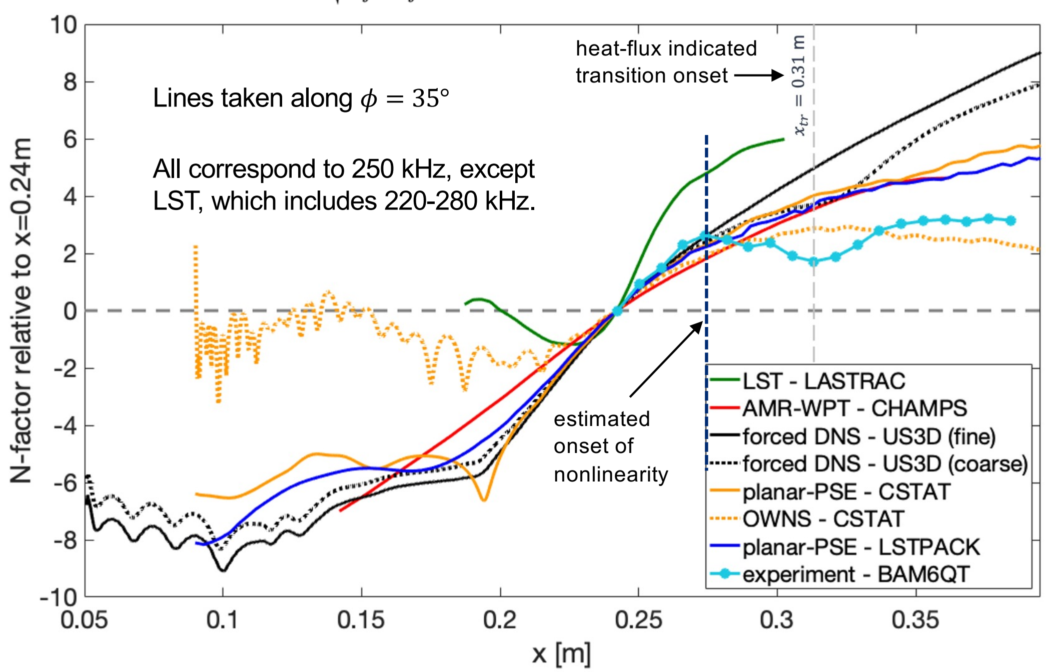
AMR-WPT prediction for various frequencies

N-factor comparison with experiment

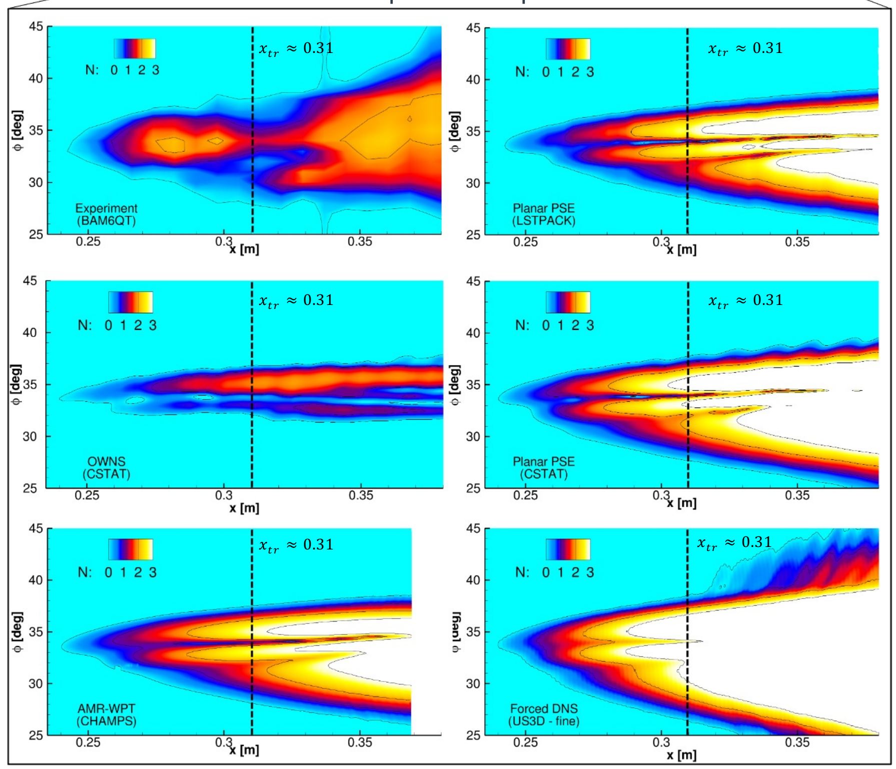


- Surface pressure fluctuations measured in experiment and from stability computations used to compute an N-factor relative to a local maximum (p'_{max}) at x=0.24m and 250 kHz.

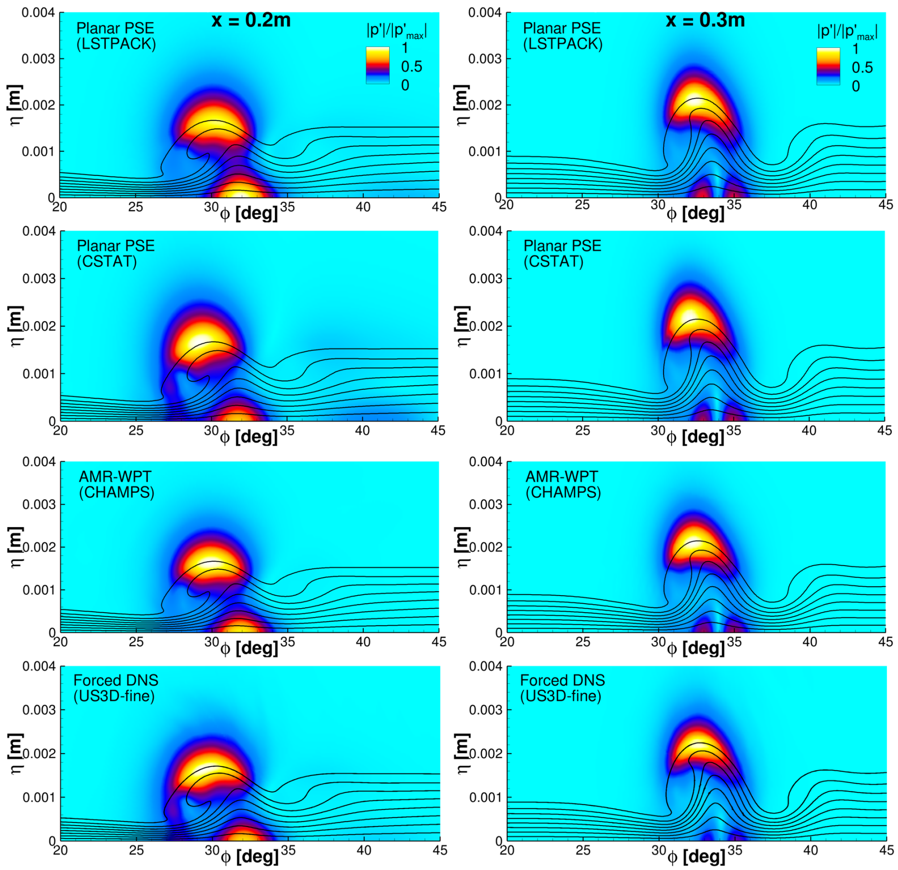
$$p'(x,\phi,f)_{\mathrm{exp}} = \sqrt{\int_{f-\Delta f}^{f+\Delta f} \mathrm{PSD}(x,\phi,f')df'}, \qquad N = ln\left(\frac{|p'|}{|p'_{\mathrm{max}}|}\right)$$



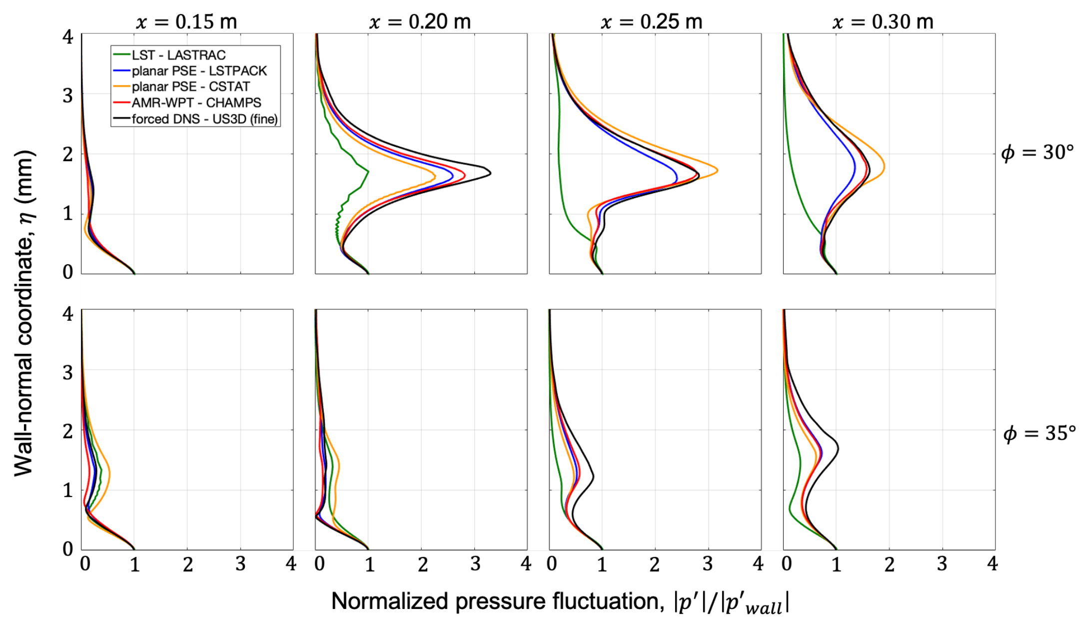
All contour plots correspond to 250 kHz



Mode Shape Comparison

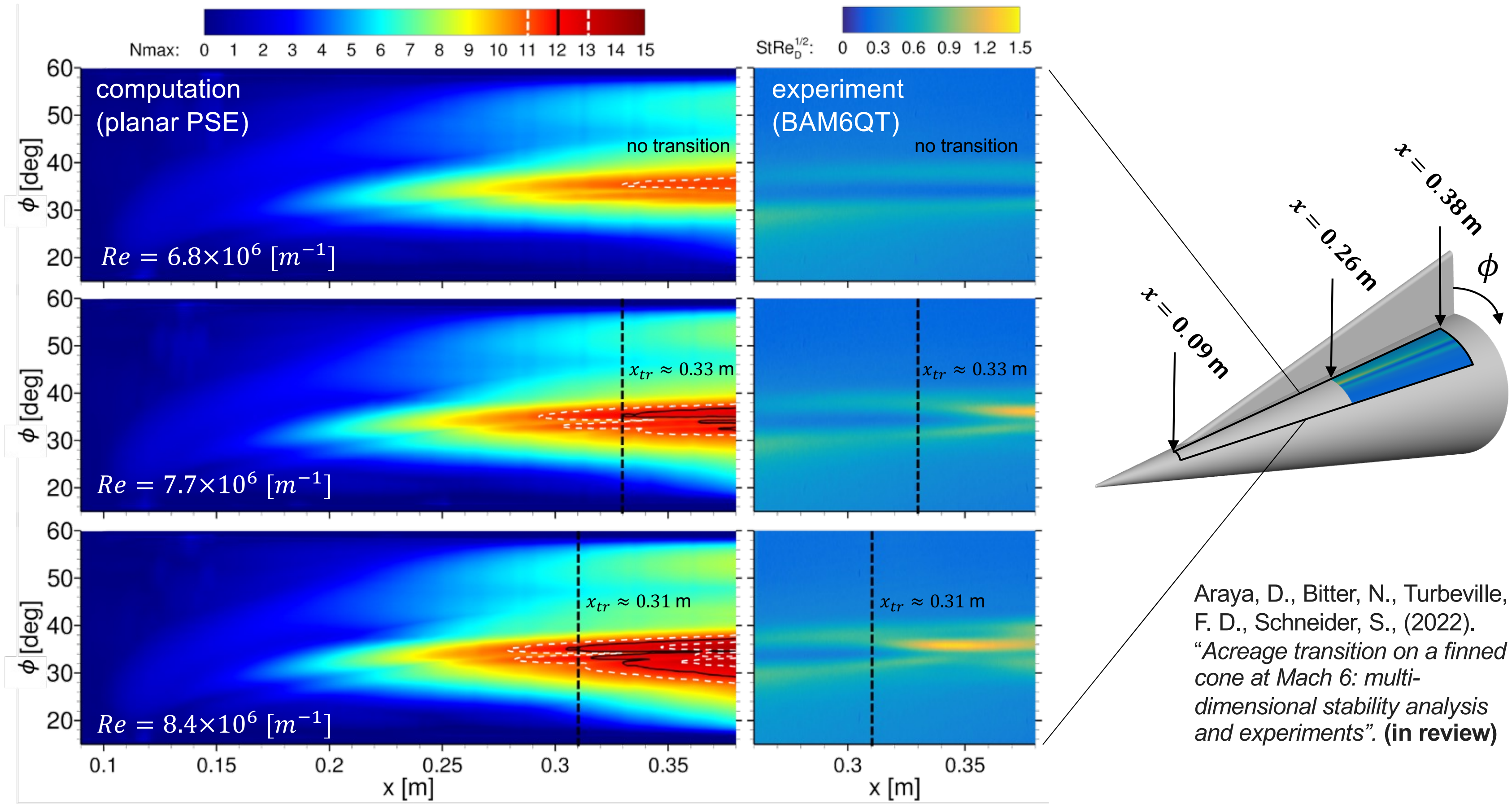


- Mode shape of the pressure fluctuations for the dominant vortex instability at 250 kHz illustrated by normalizing the computed pressure fluctuations by a local maximum.
- Instability has a unique structure with two local peaks that all except LST are able to capture.



Further investigation of other Purdue conditions

increasing *Re*



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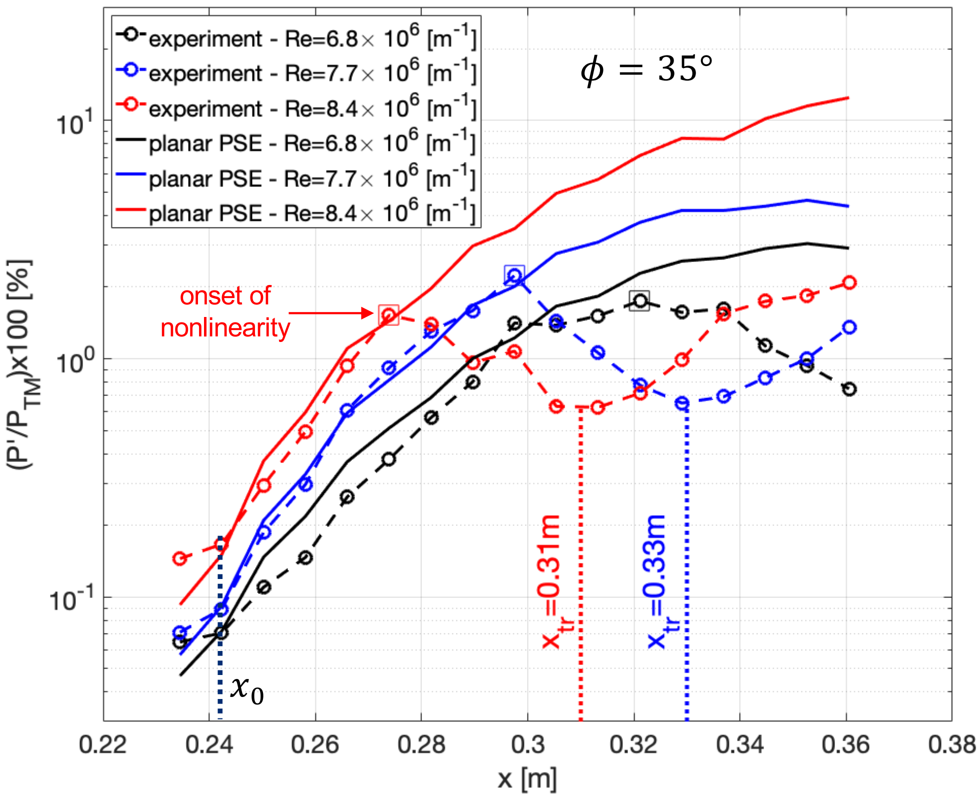
Further investigation of other Purdue conditions



- Measurement of initial pressure amplitude, $A_0(x_0)$ used to scale computed N-factors and give computed pressure amplitude, $A_i(x_i)$ as:

$$\sqrt{\frac{A_i}{A_0}} = e^{\Delta N_i} \qquad \Delta N_i = N(x_i) - N(x_0)$$

$$A_i = \left(\frac{p'}{p_{TM}}\right)_i^2$$

- **Planar PSE and measurements show good agreement in linear regime** (up to square symbols).

- Departure of measured surface pressure amplitude from linear predictions indicate maximum amplification of pressure fluctuations at ~2% of the wall pressure before transition (Note off-wall fluctuations are predicted to be higher).

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Part 2: Direct Numerical Simulation (DNS) of Hypersonic Turbulence

Approach:

- HTT leverages a companion Frontier project with overlapping objectives for turbulent DNS computations.
- Assess existing RANS model heating predictions of flight-like experiments using DNS.
- Report whether DNS agrees with experiments or RANS along with recommendations for improvements.

FY21-23 DoD HPCMP Frontier Project:
"*Direct Numerical Simulations of Turbulence at Hypervelocity Flight Conditions*"

Frontier Project synopsis:
"This HPC Frontier project will support both the basic science of hypervelocity turbulent flow and the application of turbulence models for real flight vehicles. The project will use direct numerical simulations (DNS) to identify and address deficiencies in existing turbulence models for aero-heating prediction, a key risk area for hypersonic vehicle design."

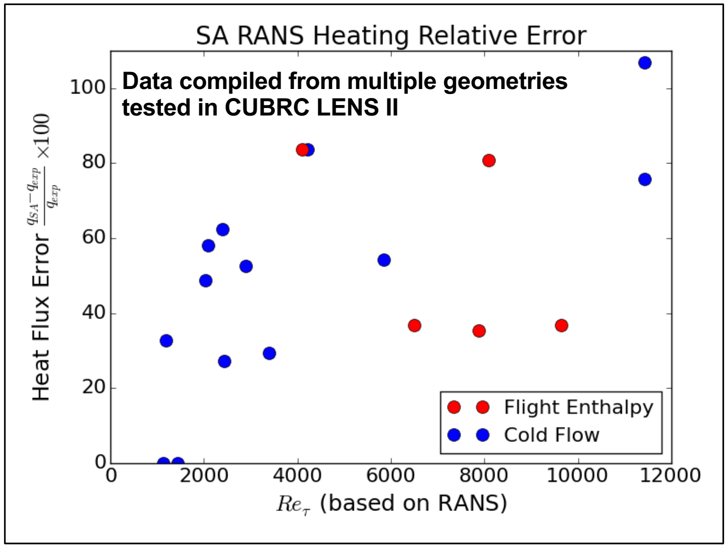
Sponsor: Dr. Eric Marineau, Program officer ONR Code 351.

Principal Investigator: Dr. Neal Bitter
Key Collaborators: Drs. Daniel Araya, Lian Duan, Micah Howard, Rodney Bowersox.

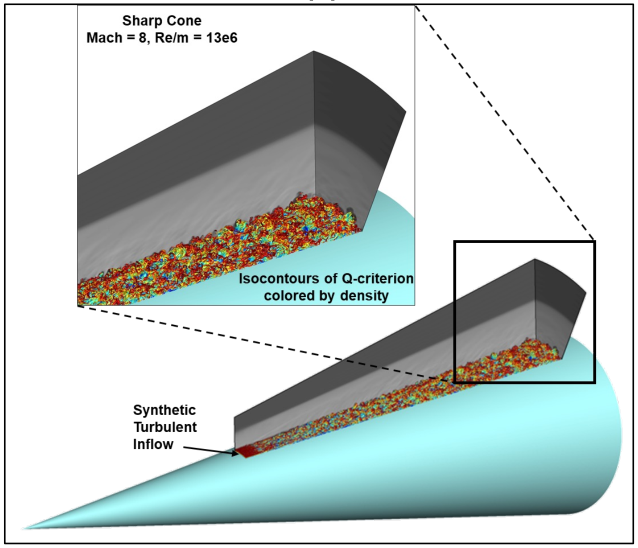
Award: >300M CPU hours to support HTT project.

Turbulent DNS Progress

- Primary turbulent DNS results for this project cannot be shown here due to distribution restrictions
- Numerous RANS vs experimental comparisons suggest inaccuracy of RANS models at high turbulent Reynolds numbers (Re_τ).
- DNS have been performed for 4 DoD programs investigating both transition (forced DNS) and turbulent heating.
- DNS performed to date agree with experiments and suggest a RANS modeling error rather than an experimental issue with turbulent heating measurement.
- Both synthetic-turbulent-inflow DNS and fully transitional DNS predict the same heat flux, suggesting insensitivity to method of turbulence establishment.



DNS Approach



Concluding remarks

- Higher fidelity (>1D) linear stability methods are necessary and sufficient to capture dominant vortex instability leading to acreage transition observed in finned-cone quiet tunnel experiments at Purdue.
- Regardless of stability prediction method used, all have nuances that could be improved and a strong parameter sensitivity – determining the most appropriate small disturbance to simulate (e.g., location, frequency, phase speed, etc.) remains a significant challenge.
- More DNS evidence suggests inaccuracy of RANS models at high turbulent Reynolds numbers (Re_τ).

Next Steps

- Completion of finned-cone publications.
- Remainder of second-year efforts at APL have shifted to analysis of exclusively limited distribution cases.
- Open to continuing to share data and collaborate with others on existing finned-cone or blunt ogive simulations.

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