

Interaction of a Tunnel-like Acoustic Disturbance Field with a Blunt Cone Boundary Layer at Mach 8

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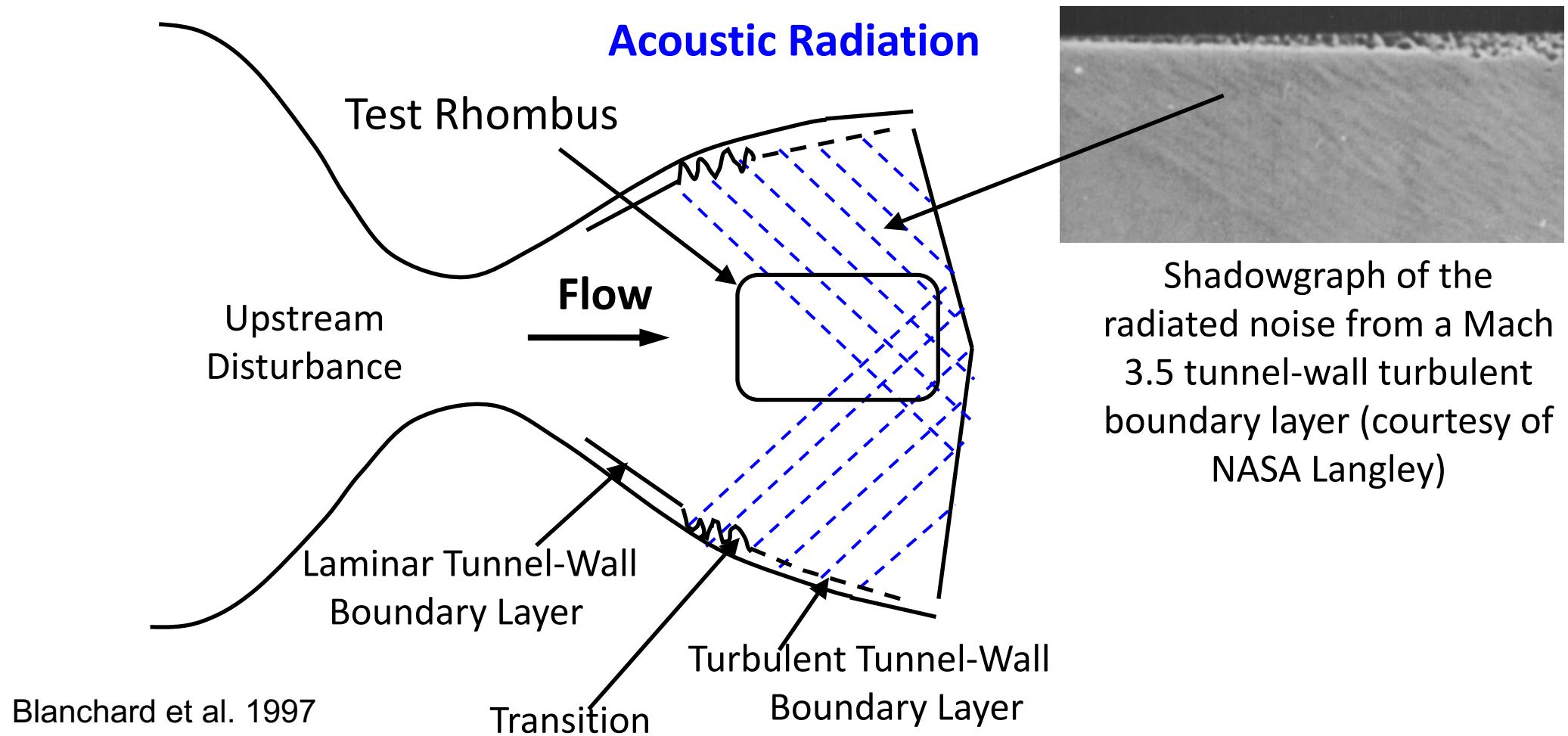
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Supported by NSF and ONR



Background

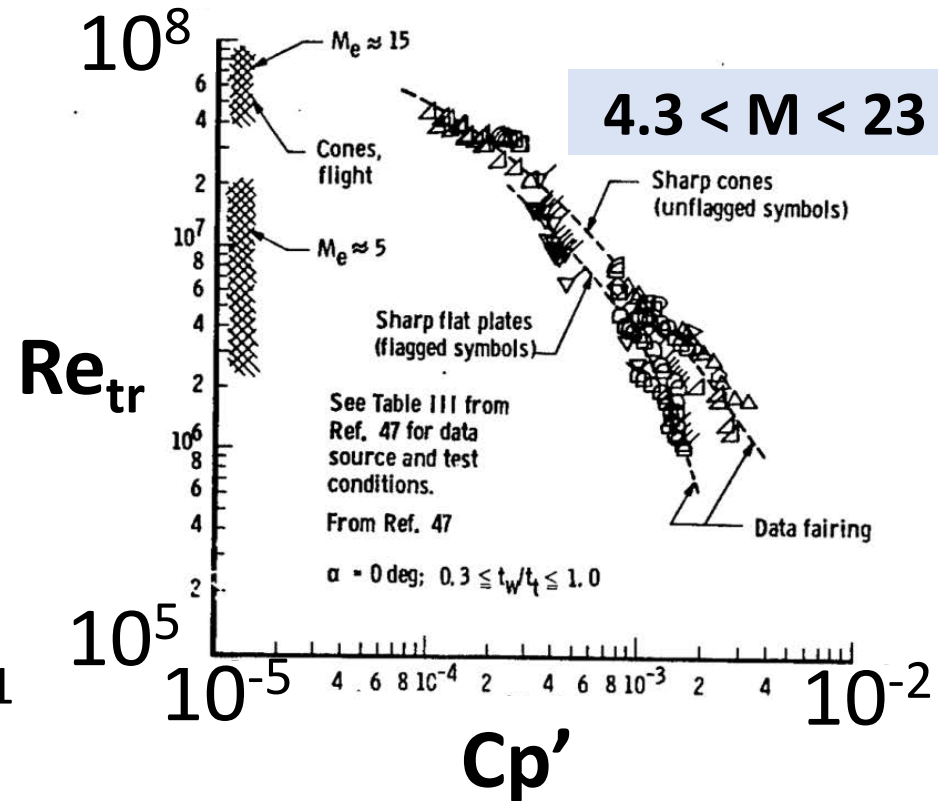
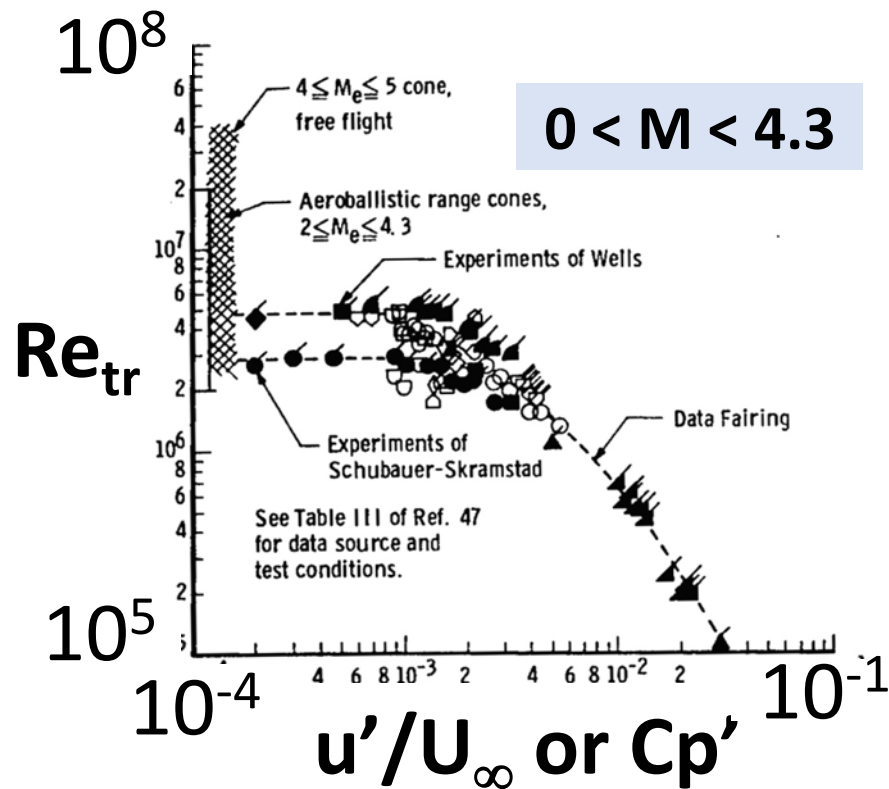
Disturbance Environment for High-Speed Wind-Tunnel Facilities



In a conventional tunnel ($M_\infty > 2.5$), tunnel noise is dominated by **acoustic radiation** from turbulent boundary layers on tunnel side-walls (*Laufer, 1964*)

Background

Boundary layer transition on a test article mounted in a high-speed tunnel is strongly influenced by high levels of background disturbances (“**Tunnel noise**”)



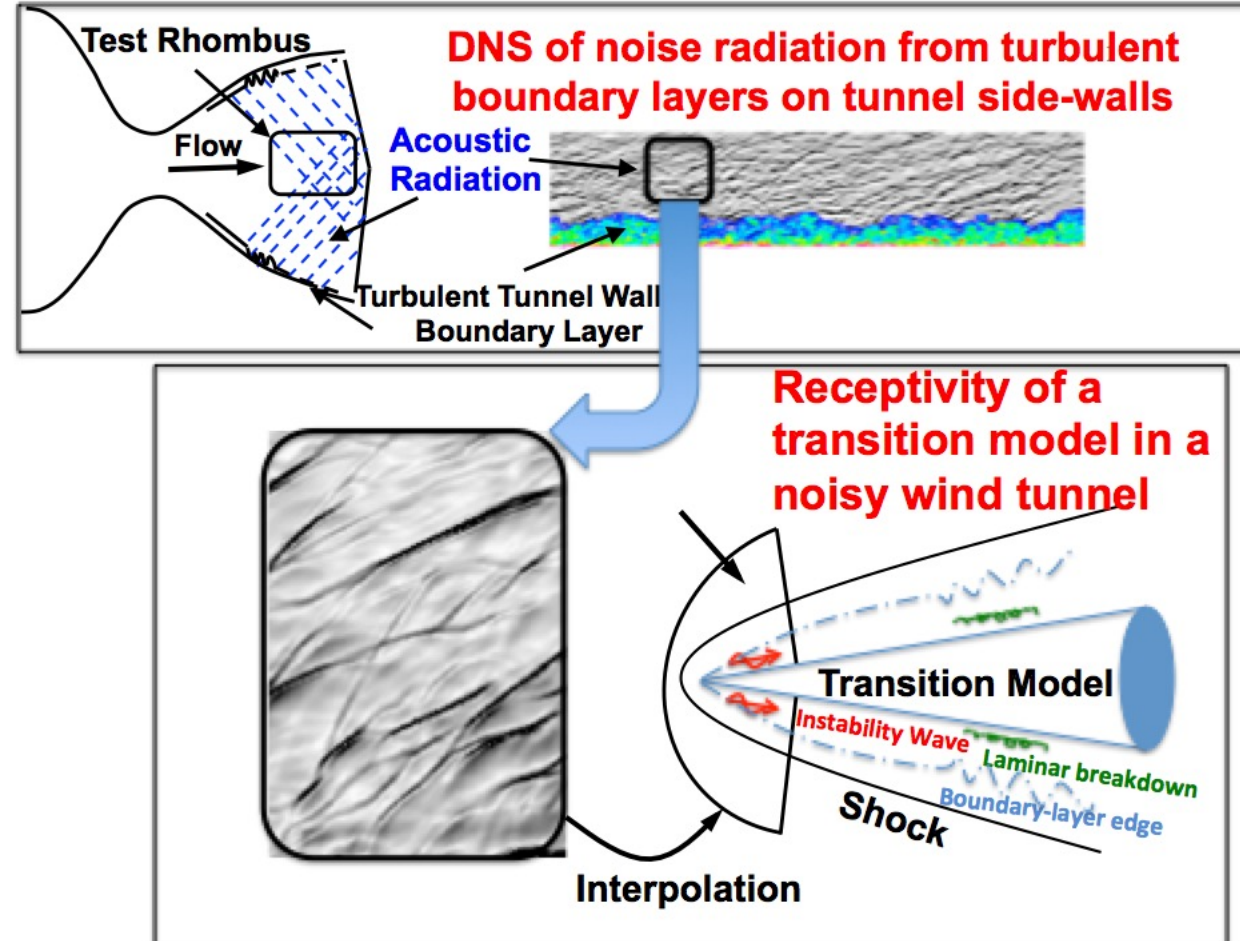
Harvey, 1978

Methodology

Mimic the transition process in the tunnel-like environment

Potential contributions:

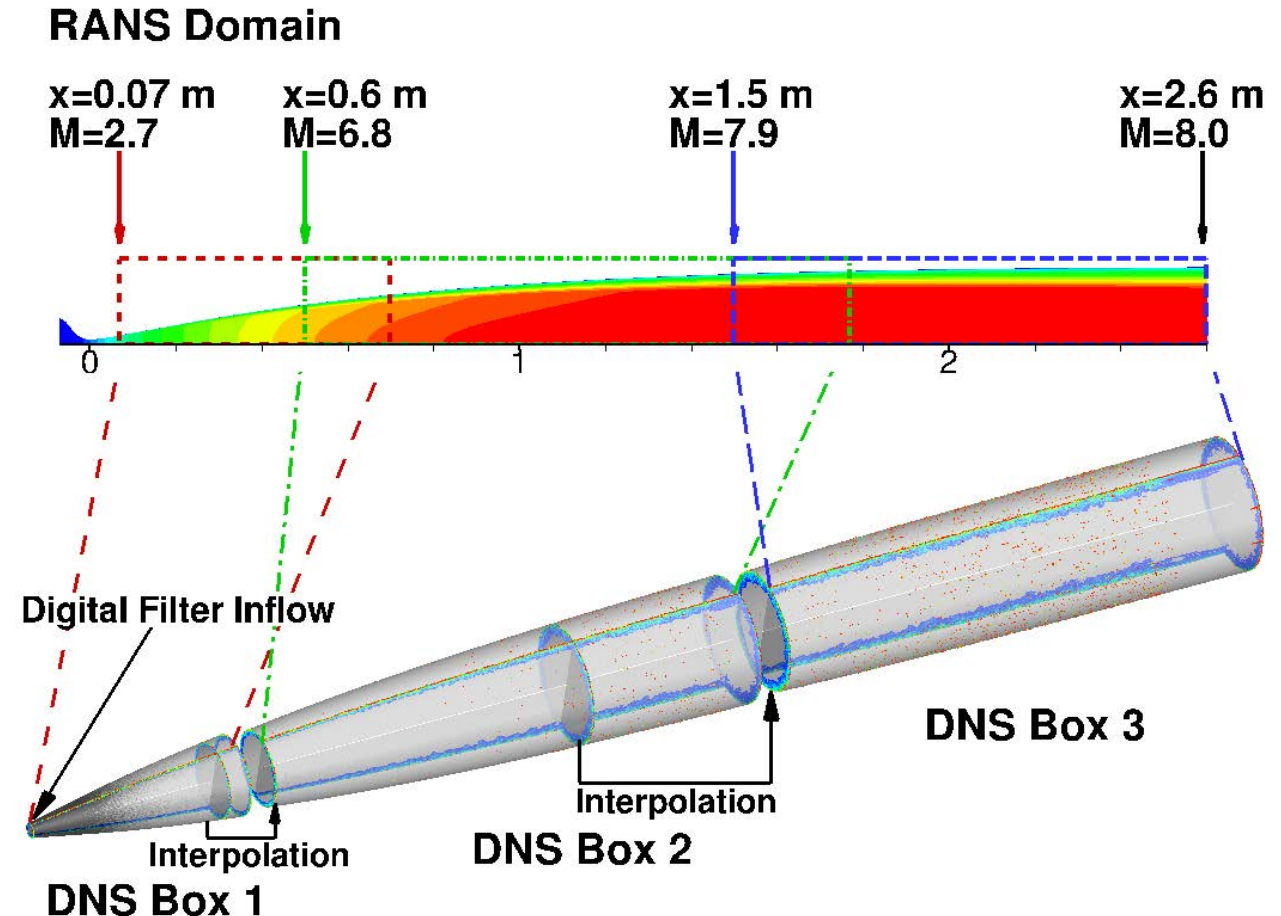
- Generate improved knowledge of receptivity process in facility-disturbance environment
- Provide the initial disturbances in hypersonic boundary layers required for conducting stability analysis.



Precursor DNS of Full-scale Nozzle of Sandia HWT-8

Nozzle Geometry & Flow Conditions

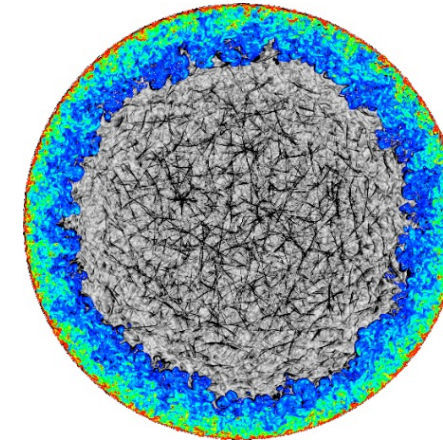
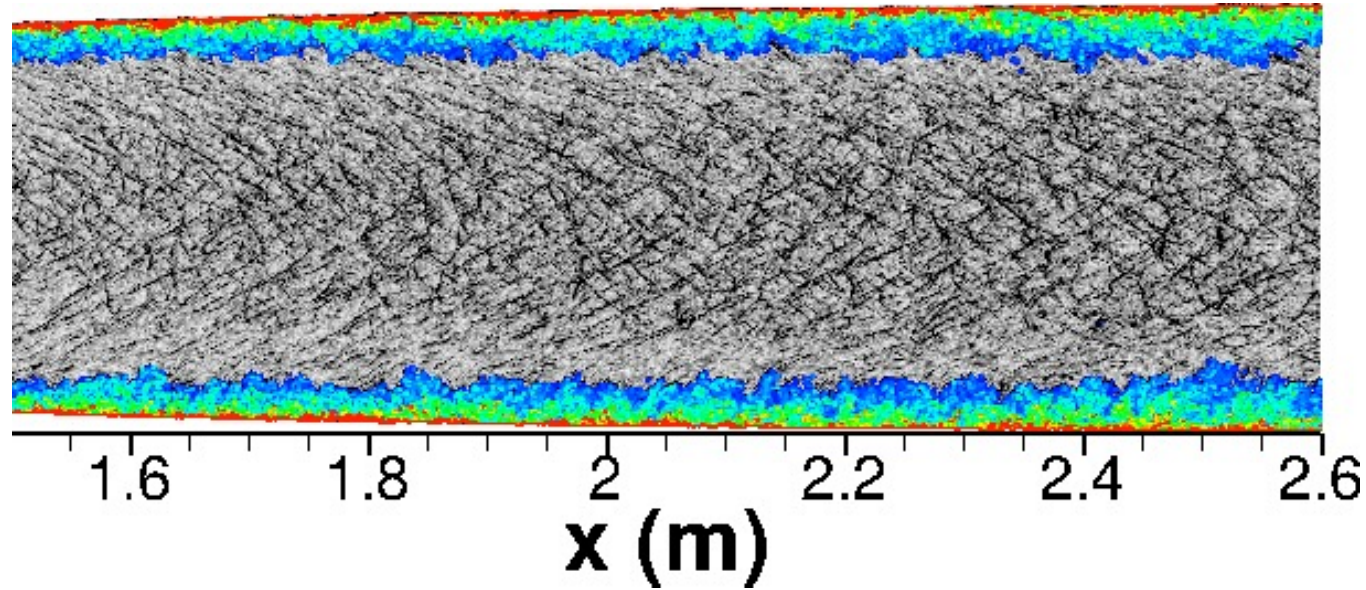
- Nozzle geometry and flow conditions match those of Sandia HWT-8
 - Nominal reservoir conditions
 - $p_0 = 4692$ kPa, $T_0 = 617$ K,
 - “Embedded” DNS method
 - DNS domain ($0.07 \text{ m} < x < 2.6 \text{ m}$) enclosed in RANS domains
 - DNS domain includes the “acoustic origin” of test section
 - DNS inflow extracted from a full-domain RANS solution obtained by Ansys Fluent
 - RANS domain ($-0.07 \text{ m} < x < 2.6 \text{ m}$)



Duan et al. 2018

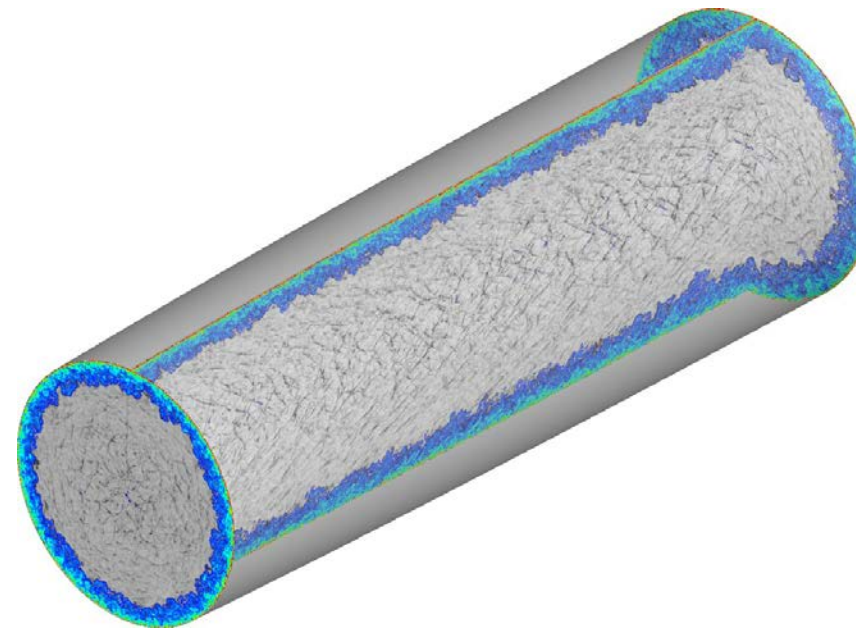
Precursor DNS of Full-scale Nozzle of Sandia HWT-8

Visualization of DNS Flowfield



$x = 2.336 \text{ m}$

Grayscale: numerical schlieren
Colors: vorticity magnitude



$1.5 \text{ m} < x < 2.6 \text{ m}$

“Tunnel-like” Acoustic Disturbance Generation

- “Tunnel-like” acoustic disturbance generation
 - Represent the broadband tunnel noise in the free stream by an acoustic model with an ansatz of plane acoustic waves

$$q'(\mathbf{x}, t) = \sum_{j=1}^N \hat{q}_j \hat{p}_j(\mathbf{k}_j, \omega) e^{-i(\mathbf{k}_j \cdot \mathbf{x} + \omega_j t + \phi_j)} + c. c.$$

With $q' = (p'_{1,\infty}, \rho'_{1,\infty}, u'_{1,\infty}, v'_{1,\infty}, w'_{1,\infty}, T'_{1,\infty})^T$

$$\hat{q}_j = \left(1, \frac{1}{\bar{c}_{1,\infty}^2}, \frac{1}{\bar{\rho}_{1,\infty} \bar{c}_{1,\infty}} \left(\frac{k_{x,j}}{\|\mathbf{k}_j\|} \right), \frac{1}{\bar{\rho}_{1,\infty} \bar{c}_{1,\infty}} \left(\frac{k_{y,j}}{\|\mathbf{k}_j\|} \right), \frac{1}{\bar{\rho}_{1,\infty} \bar{c}_{1,\infty}} \left(\frac{k_{z,j}}{\|\mathbf{k}_j\|} \right), \frac{(\gamma-1)\bar{T}_{1,\infty}}{\gamma \bar{p}_{1,\infty}} \right)^T$$

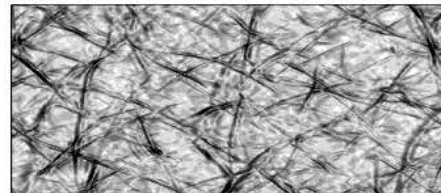
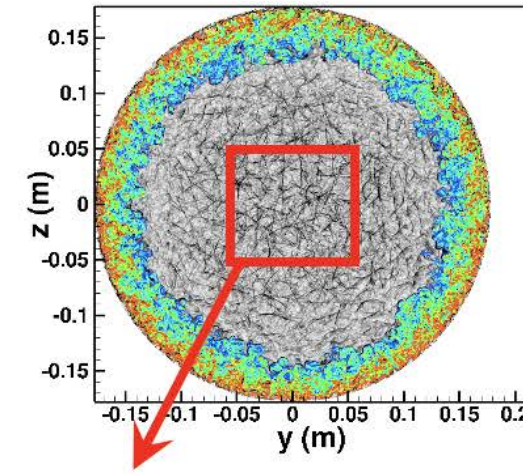
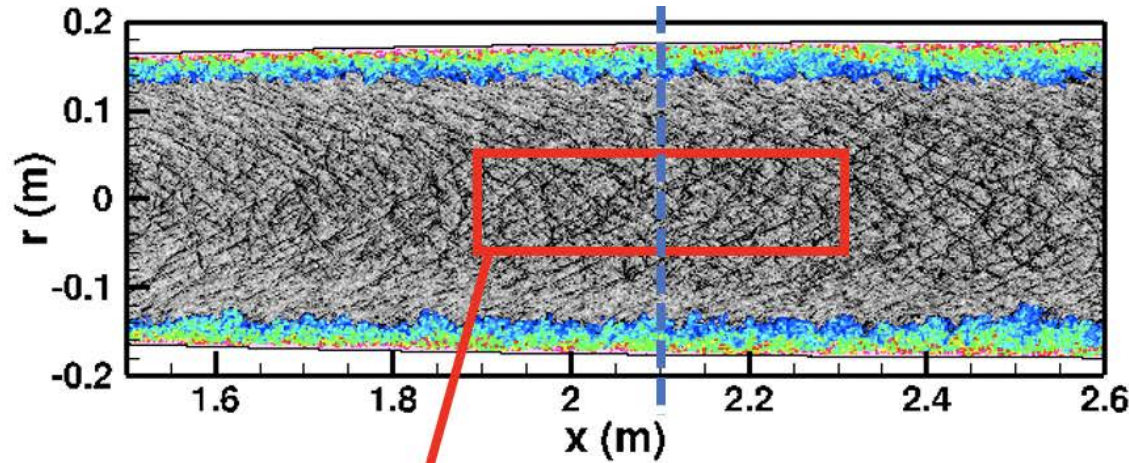
- Apply the dispersion relation for acoustic waves to relate the angular frequency ω_j to wavenumber $\mathbf{k}_j$

$$\omega_j = \bar{\mathbf{u}}_{1,\infty} \cdot \mathbf{k}_j \pm \bar{c}_{1,\infty} \|\mathbf{k}_j\|$$

The plus-minus sign ($\pm$) indicates that the group velocity of the acoustic waves can be faster or slower than the mean flow velocity

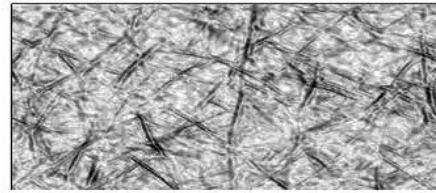
- “slow” acoustic waves (-): $\omega_j = \bar{\mathbf{u}}_{1,\infty} \cdot \mathbf{k}_j - \bar{c}_{1,\infty} \|\mathbf{k}_j\|$
- “fast” acoustic waves (+): $\omega_j = \bar{\mathbf{u}}_{1,\infty} \cdot \mathbf{k}_j + \bar{c}_{1,\infty} \|\mathbf{k}_j\|$
- The radiated noise from the nozzle-wall turbulent boundary layer dominated by “slow” acoustic waves
- Calibrate the remaining unknown parameters $(\mathbf{k}_j, \hat{p}_j, \phi)$ in the tunnel noise model using the precursor empty-tunnel DNS data
- Interpolate the generated acoustic disturbances from the Cartesian domain into the cylindrical domain
 - for the follow-on DNS involving the cone

“Tunnel-like” Acoustic Disturbance Generation

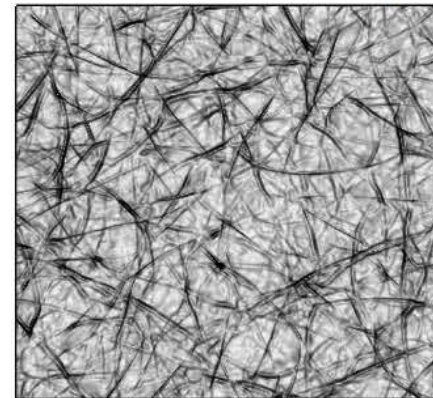


DNS (x-r plane)

extract
reconstruct
→

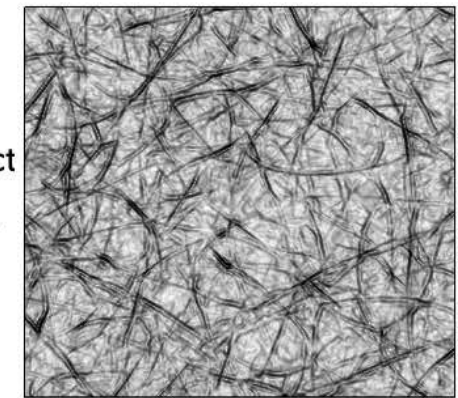


Acoustic Model (x-r plane)



DNS (y-z plane)

extract
reconstruct
→

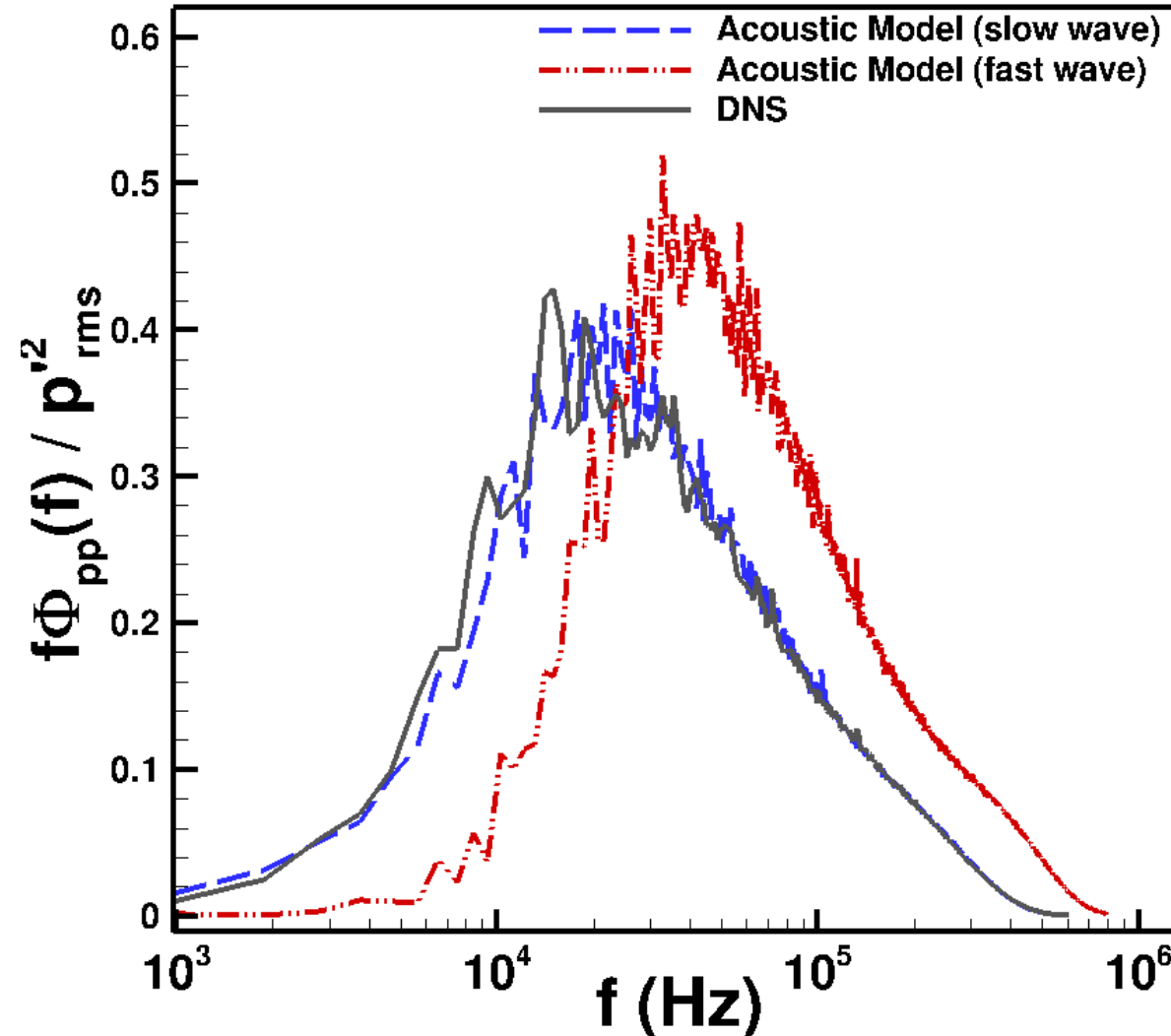


Acoustic Model (y-z plane)

- Instantaneous acoustic structures of the modeled acoustic disturbances matched well with those computed by DNS

“Tunnel-like” Acoustic Disturbance Generation

- Very good agreement in Power Spectral Density (PSD) is achieved between the acoustic model with the slow-acoustic-wave assumption and the precursor nozzle-DNS data
 - reconfirming the dominance of slow acoustic waves



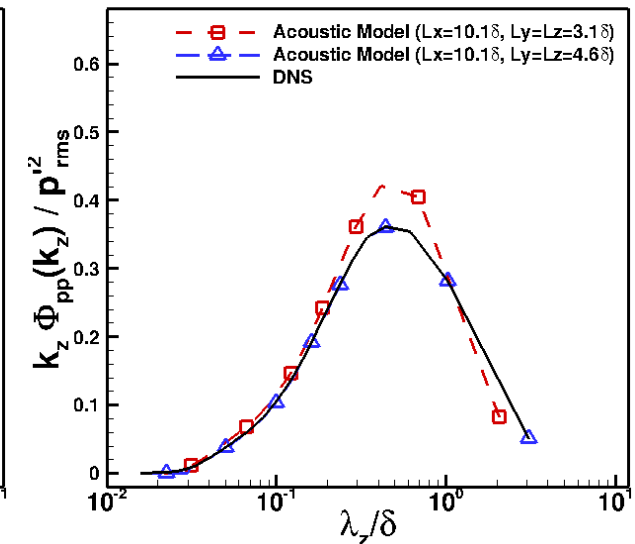
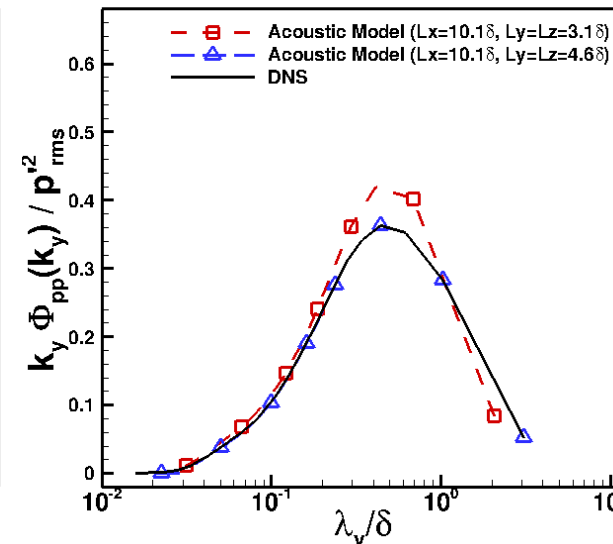
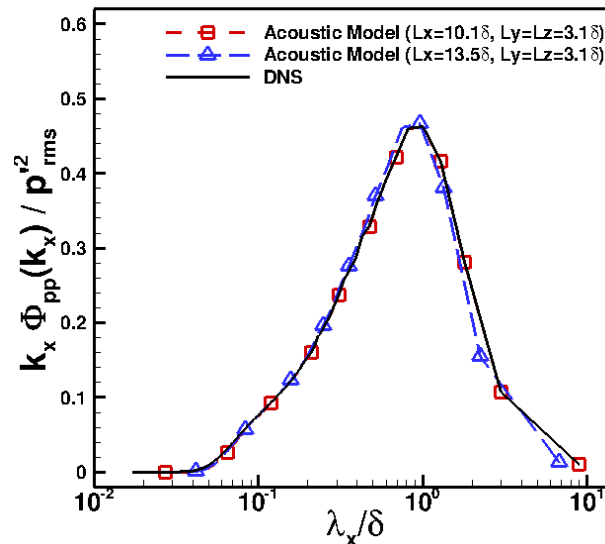


“Tunnel-like” Acoustic Disturbance Generation

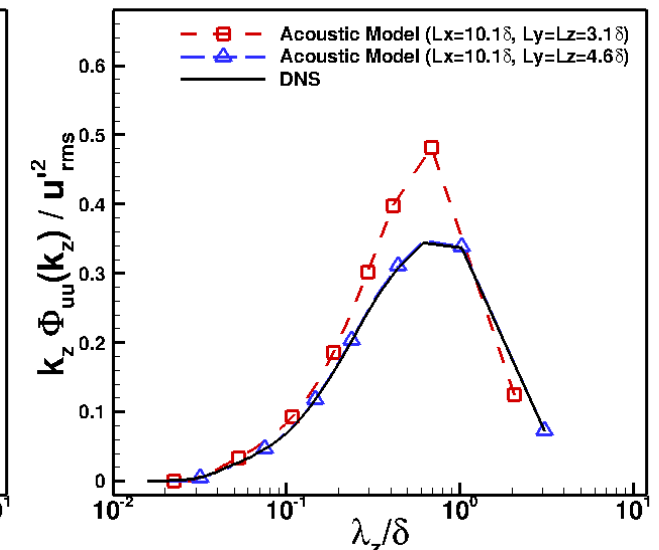
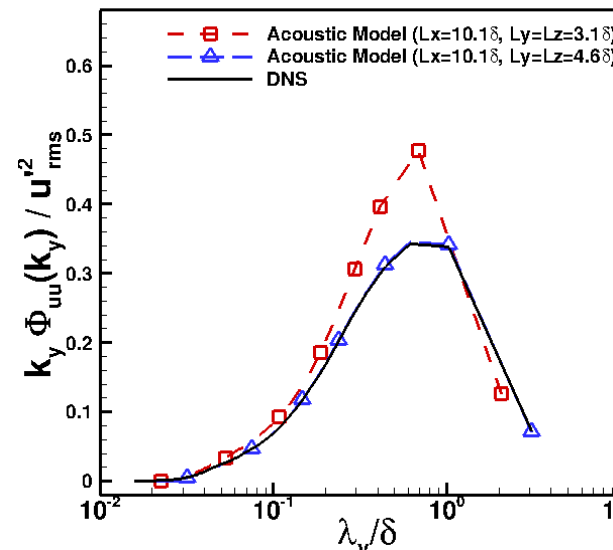
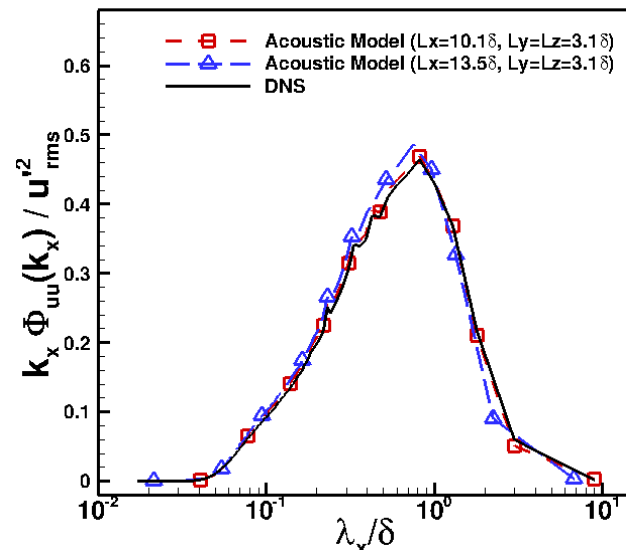


- The wavenumber spectra of the modeled acoustic disturbances (calibrated with data from a large enough domain size) matched well with those computed by the wind-tunnel nozzle DNS

Pressure
wavenumber



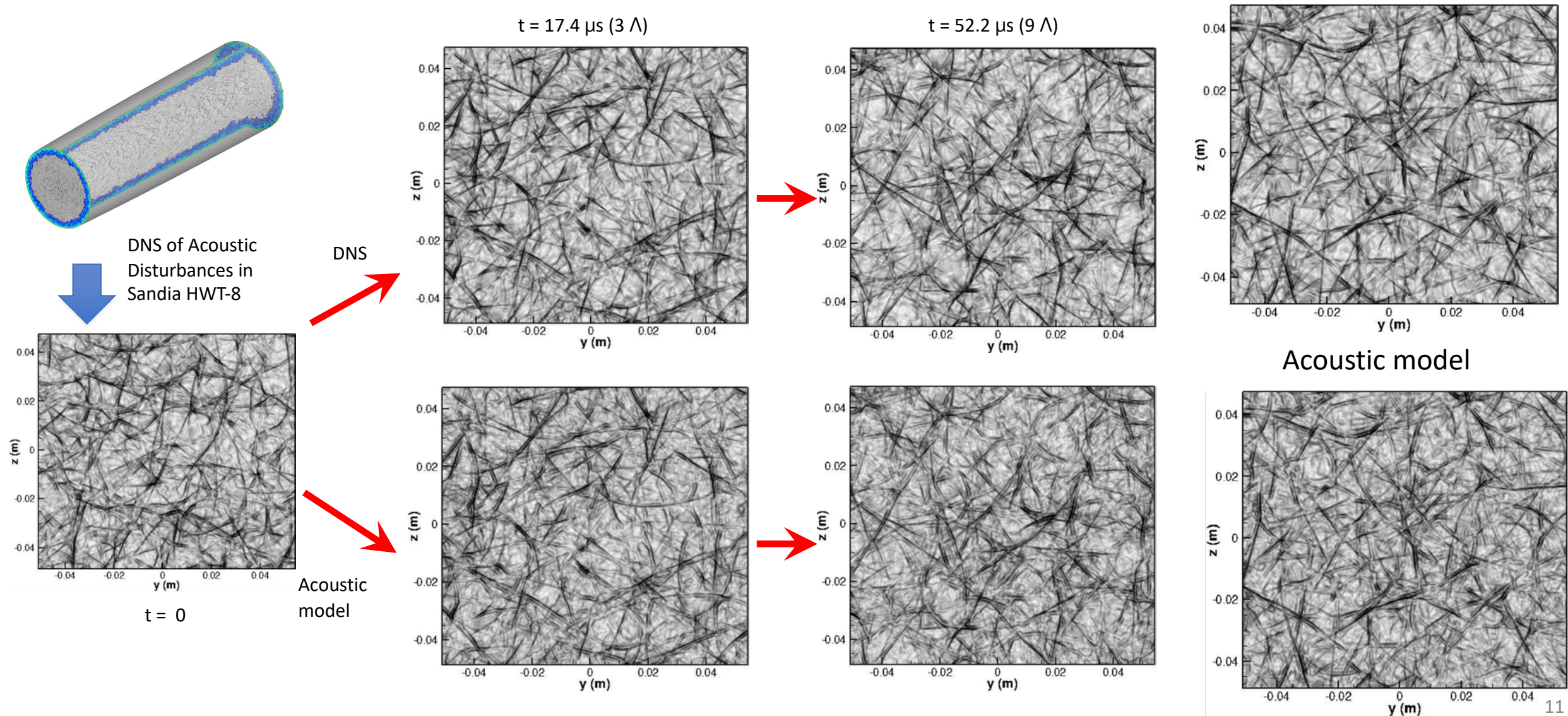
Streamwise velocity
wavenumber





“Tunnel-like” Acoustic Disturbance Generation

- Apparent similarity in the evolution of the instantaneous acoustic structures between the model and DNS
- Stochasticity of the freestream acoustic field very well preserved by the model

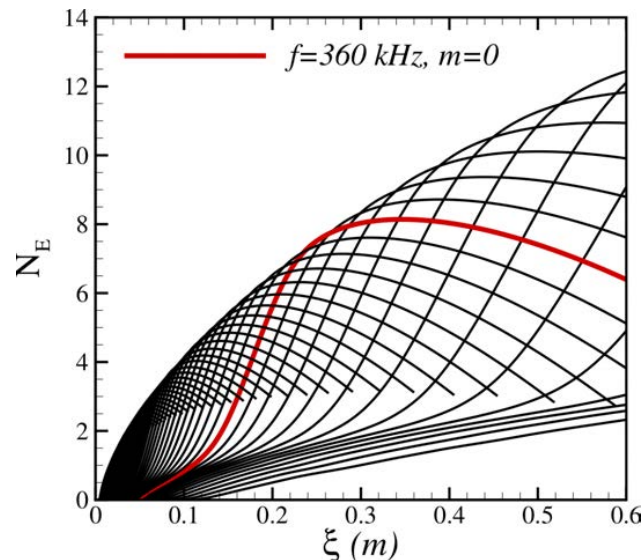


Results

- Hypersonic boundary layer over a 7° half-angle cone at Mach 8 is investigated
- The results are divided into three parts:

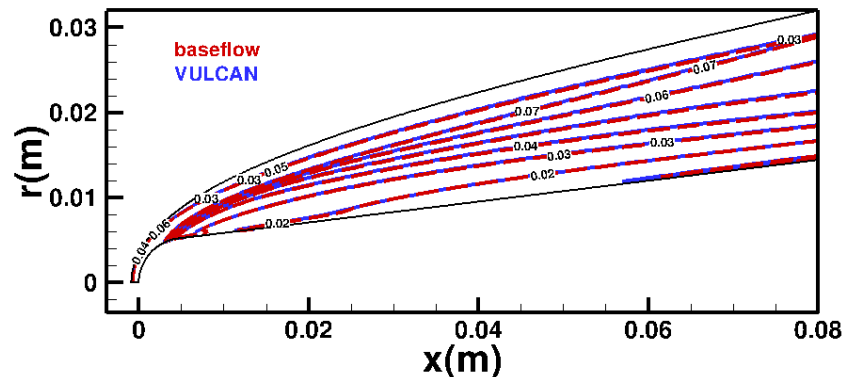
Linear instability analyses

- Modal analysis
 - Sharp cone ($R_n = 0.05$ mm)
 - Blunt cone ($R_n = 5.2$ mm)
- Nonmodal analysis
 - Blunt cone ($R_n = 5.2$ mm)



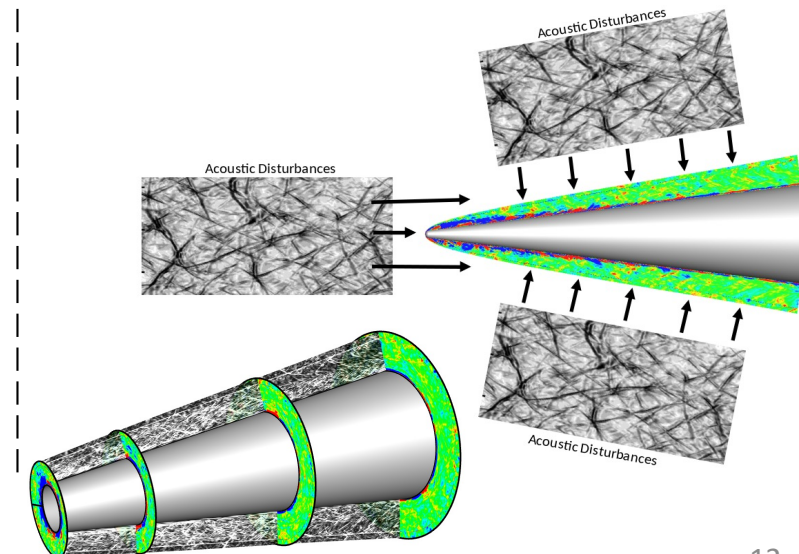
2D axisymmetric results

- Base flow computation
- Comparison between DNS and modal stability results for sharp cones
- Comparison between DNS and nonmodal stability results for blunt cone
 - $R_n = 0.05$ mm and 0.5 mm



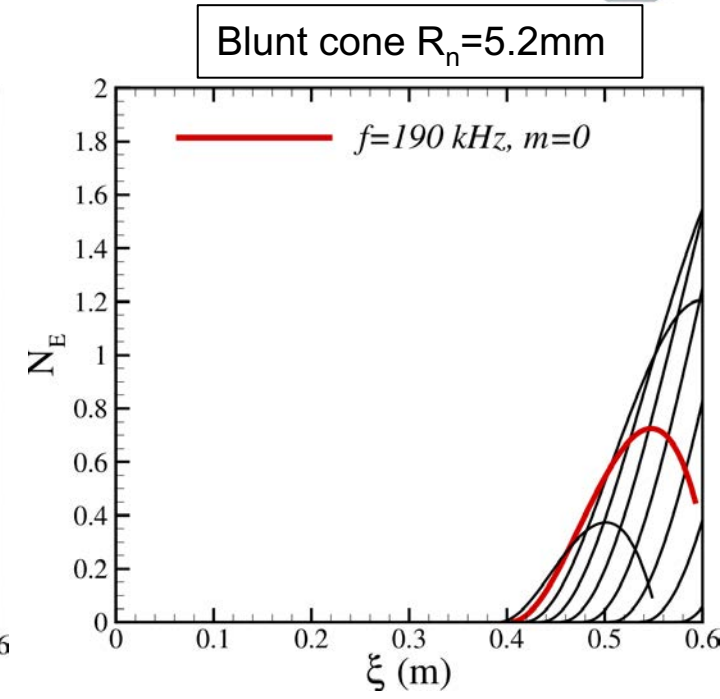
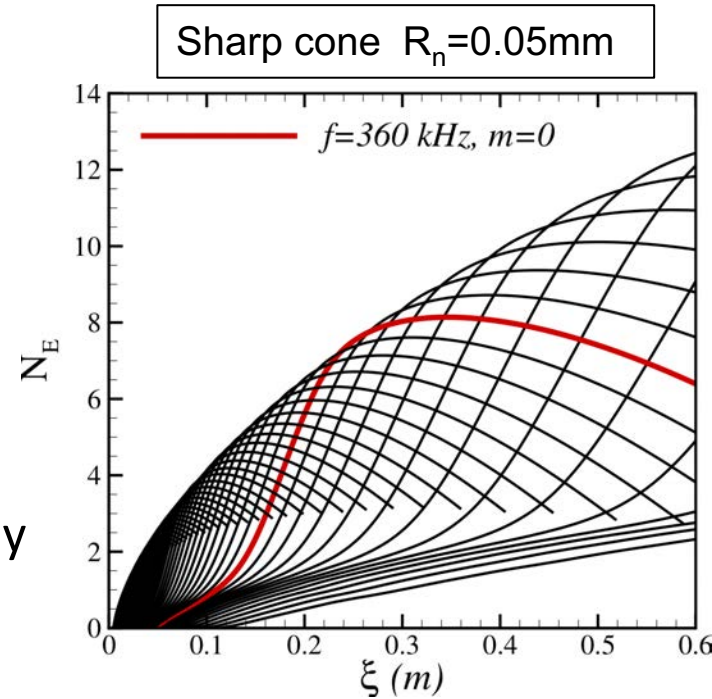
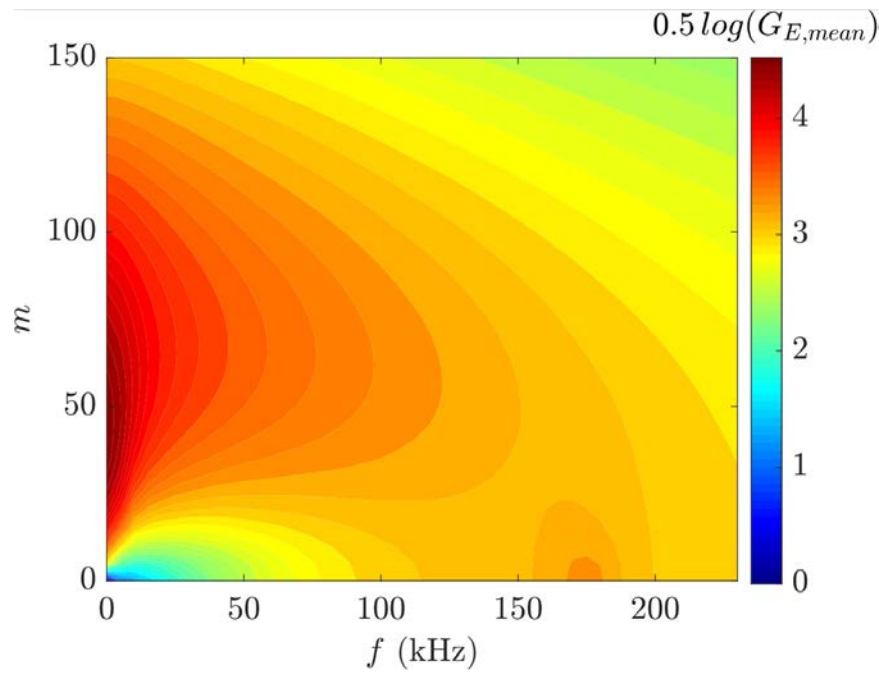
3D DNS of a blunt cone

- The results of a 3D simulation for a blunt cone
 - $R_n = 5.2$ mm
- Tunnel acoustic disturbances are used at the freestream



Results: Modal and Nonmodal Instability Analysis

- Axisymmetric geometries at a zero degrees angle of attack
- Basic state is independent of the azimuthal coordinate
- Harmonic linearized Navier-Stokes equations
- Right figures shows N-factor of planar second Mack mode waves ($m=0$)
- Amplification of Mack mode waves is drastically reduced by the blunt nose tip



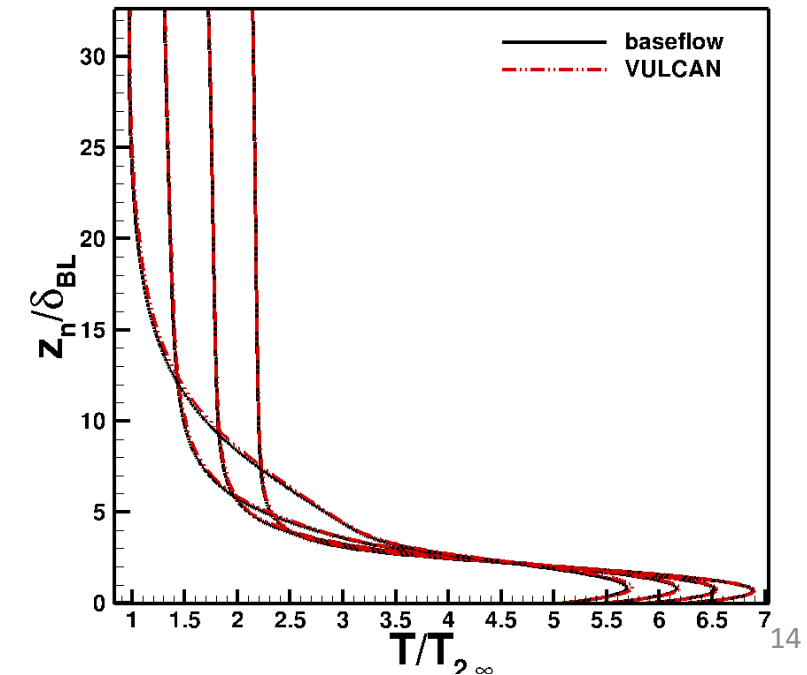
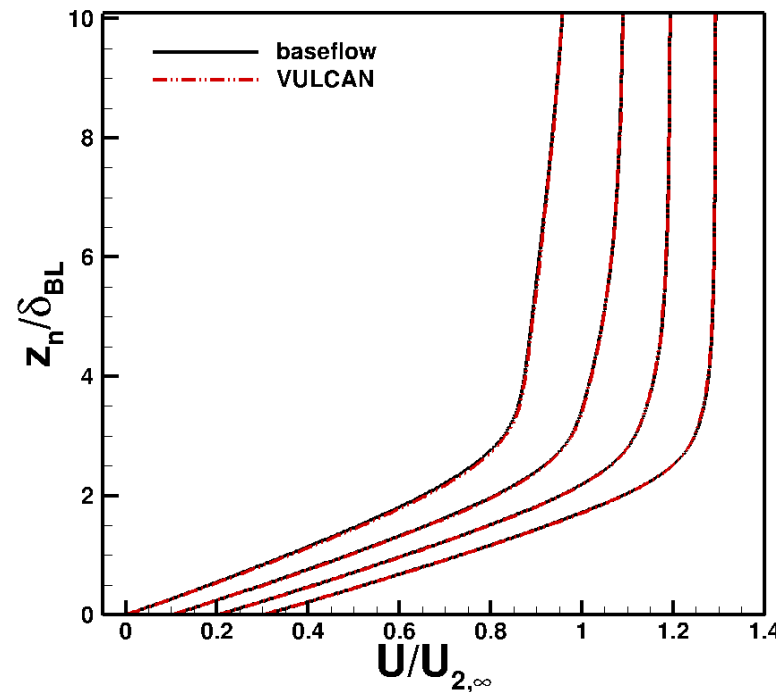
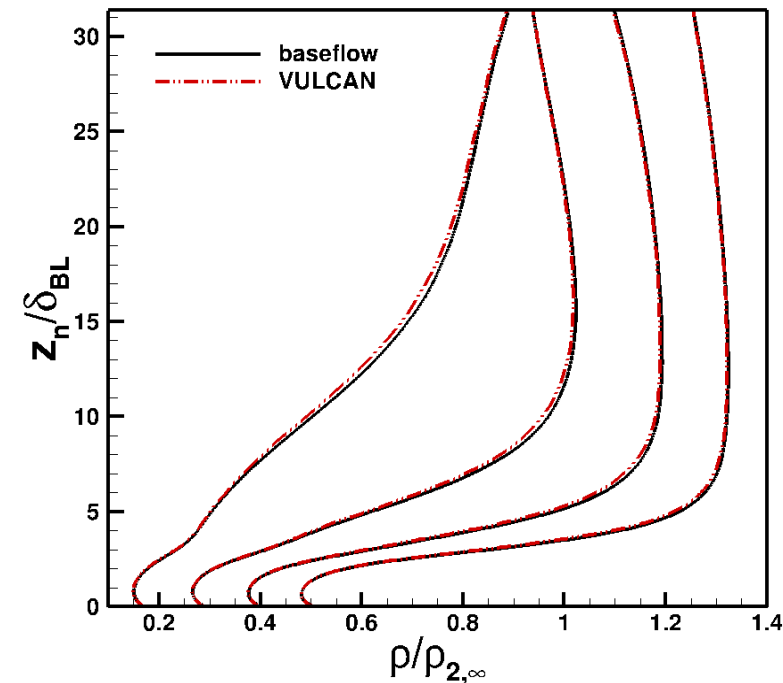
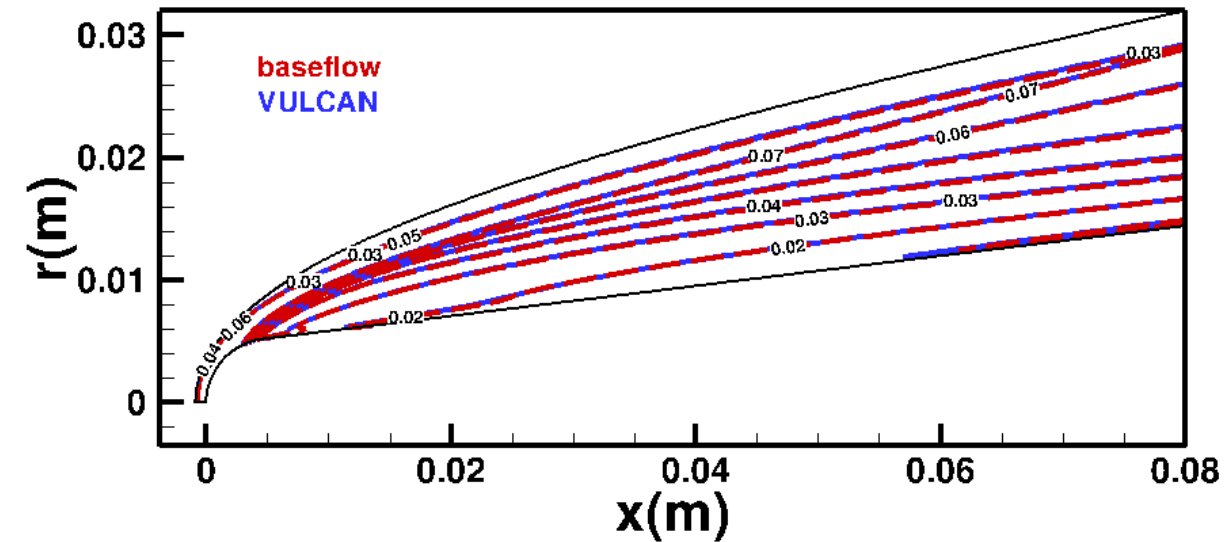
- The first neutral location is delayed up to 0.4m
- The N-factor values along the blunt cone length are 1.5 which is too low to lead to transition via purely modal amplification
- Left figure shows the nonmodal amplification for the blunt cone only
- Maximum energy gain is for stationary disturbances ($f = 0$ kHz)
- There is an additional peak for $m = 0$ and $f = 175$ kHz



Results: Two-Dimensional Axisymmetric DNS

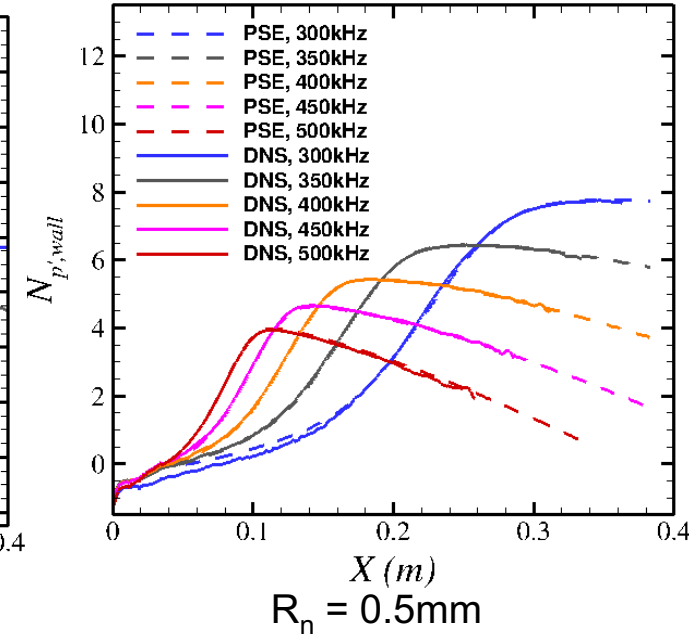
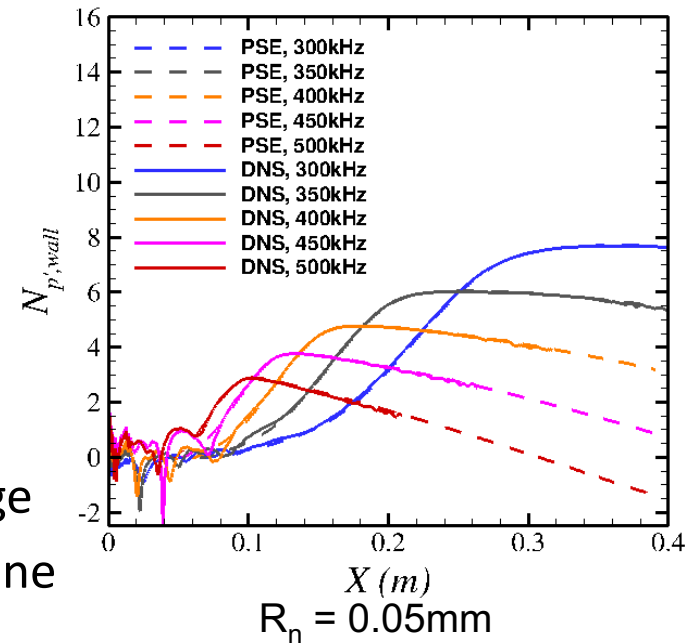


- Blunt cone with $R_n = 5.2$ mm
- Comparison between the laminar basic state computed by two different solvers:
 - 7th-order finite difference WENO based DNS code
 - 2nd-order finite volume VULCAN flow solver
- Profiles at $x = 0.1, 0.2, 0.3$ and 0.4 m

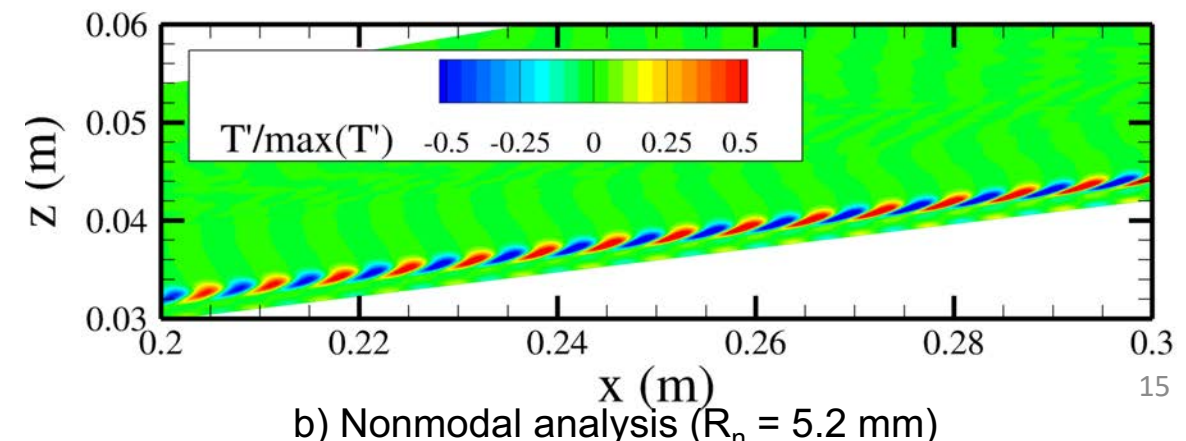
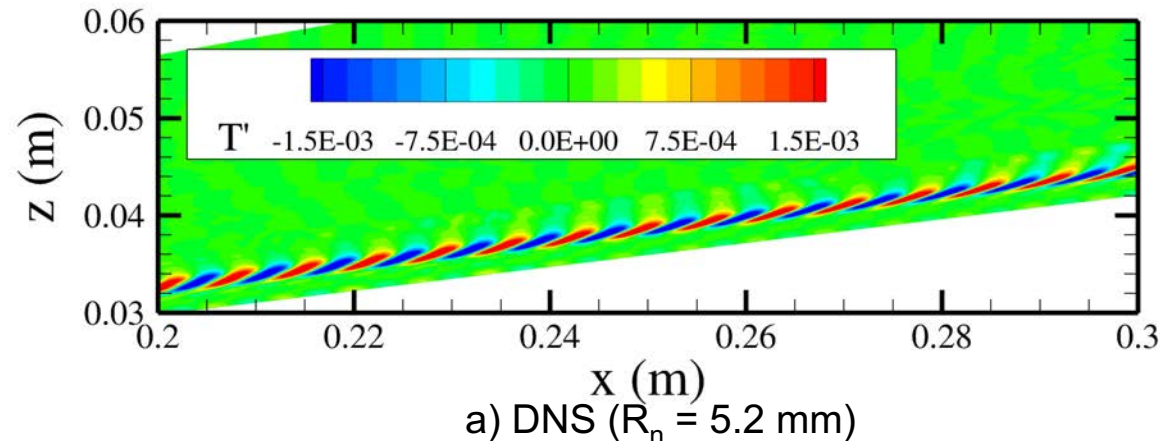


Results: Two-Dimensional Axisymmetric DNS

- Two small nose radii $R_n = 0.05\text{mm}$ and 0.5mm
- Instability over sharp cone is dominated by Mack's second modes waves (acoustic waves in nature)
- N factors can be based on wall-pressure signal
- Excellent agreement between DNS and PSE results
- Small difference between the two cases
 - Similar growth factors relative to the leading edge
 - Similar N-factor values near the middle of the cone



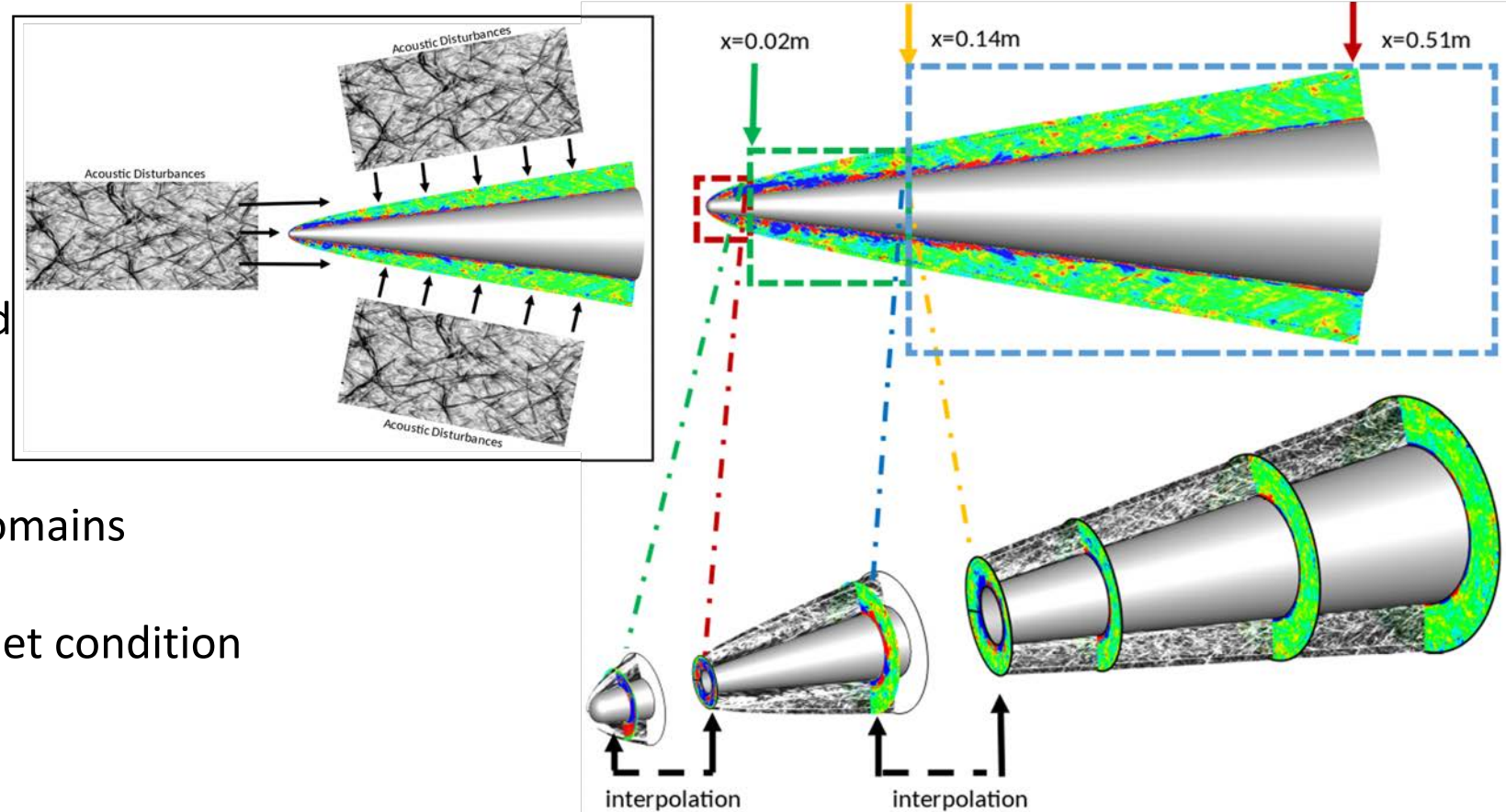
- Instantaneous contours of temperature fluctuation at $f = 150\text{ kHz}$ for the blunt cone $R_n = 5.2\text{mm}$
- Strong similarities between DNS and nonmodal stability results
 - Wall normal location and streamwise wavelength



DNS of Mach 8 Blunt Cone in a Digital Wind Tunnel

Numerical Setup for the 3D case

- 7° half-angle cone at Mach 8
- Nose radius (R_n): 5.2mm
- Acoustic disturbances are imposed at all freestream boundary
- The domain is divided into 3 subdomains
- Interpolation is done to provide inlet condition

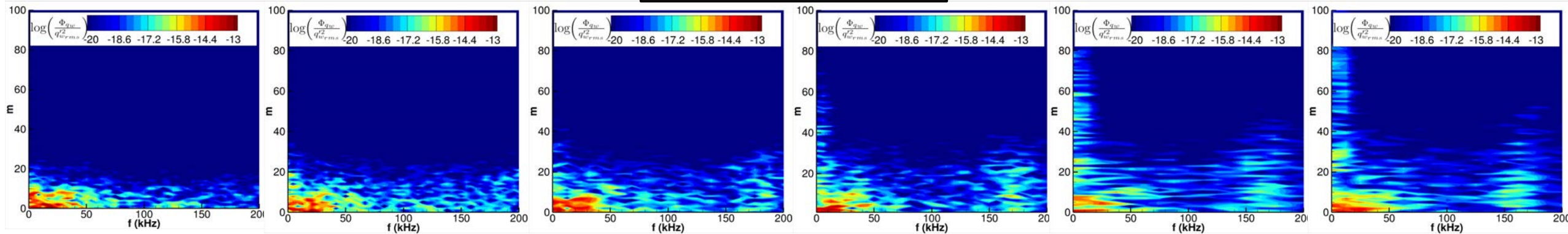


Case	$N_x \times N_\theta \times N_r$	x (m)	$\Delta x^+_{\min}$	$\Delta x^+_{\max}$	$(r\Delta\theta)^+_w$	$\Delta z^+_{n,w}$	$\Delta z^+_{n,e}$
Box 1	2800 x 256 x 1440	-0.0061 - 0.02	0.23	0.23	3.82	0.11	0.16
Box 2	1050 x 1024 x 1440	0.01 – 0.14	0.23	4.72	3.13	0.26	0.39
Box 3	2100 x 1024 x 1440	0.13 – 0.51	4.72	4.72	6.22	0.37	0.55

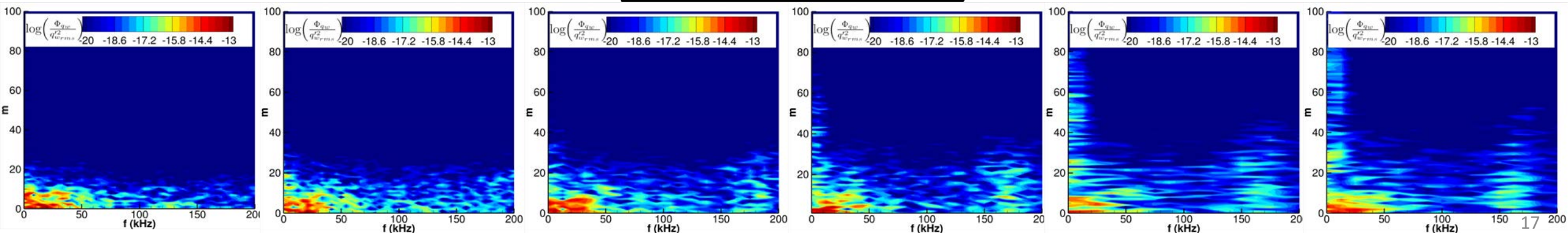
Results: Three-Dimensional DNS of Blunt Cone with Tunnel-Like Acoustic Disturbance

- Frequency/azimuthal-wavenumber (f-m) spectrum at different axial locations
- Highest values are generally confined to low frequency range up to around 50 kHz
- Emergence of a secondary peak at higher frequencies in the range of 150 to 200 kHz and m lower than 20
- The nonmodal instability analysis predicts a similar peak

Wall-pressure fluctuation



Surface heat-flux fluctuation



a) $x = 0.15m$

b) $x = 0.20m$

c) $x = 0.25m$

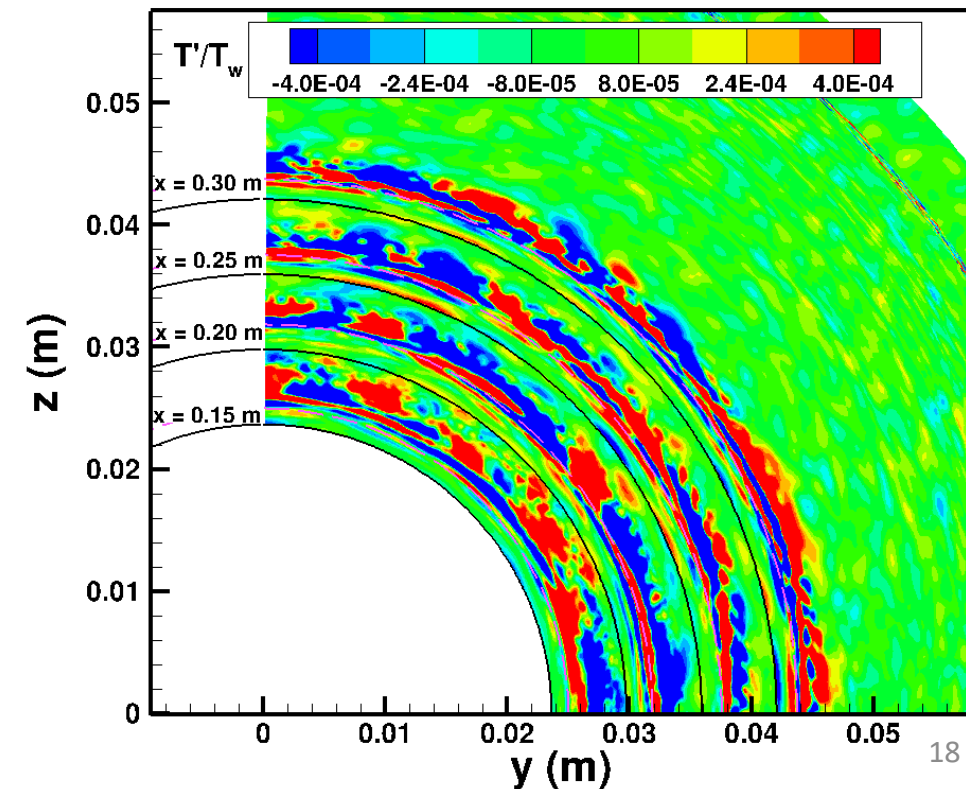
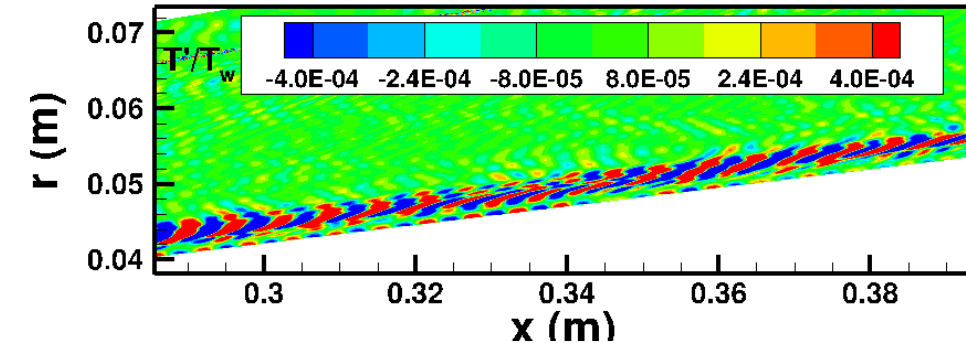
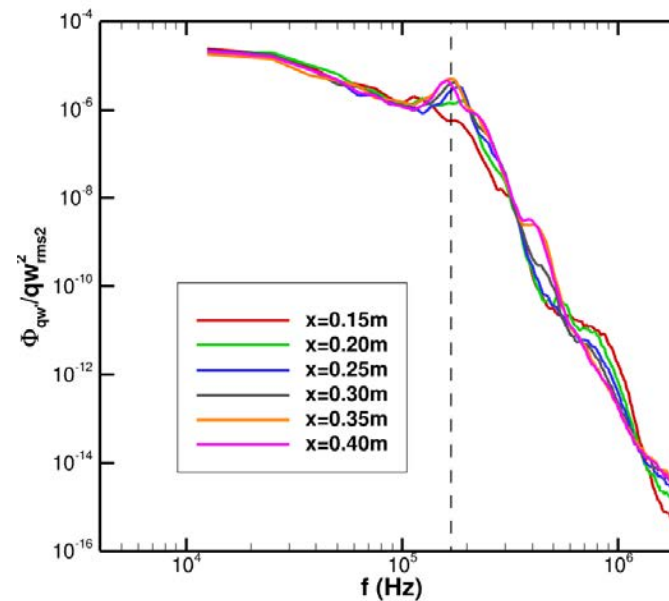
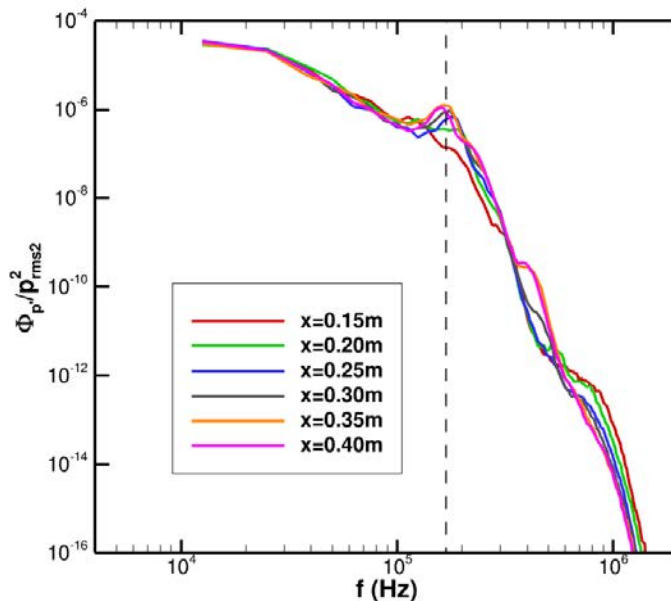
d) $x = 0.30m$

e) $x = 0.35m$

f) $x = 0.40m$

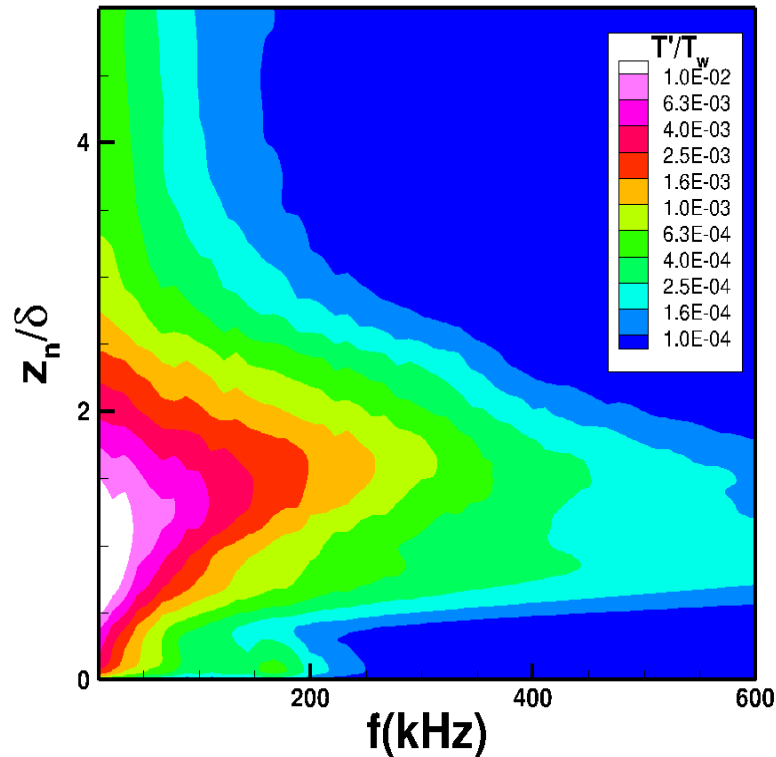
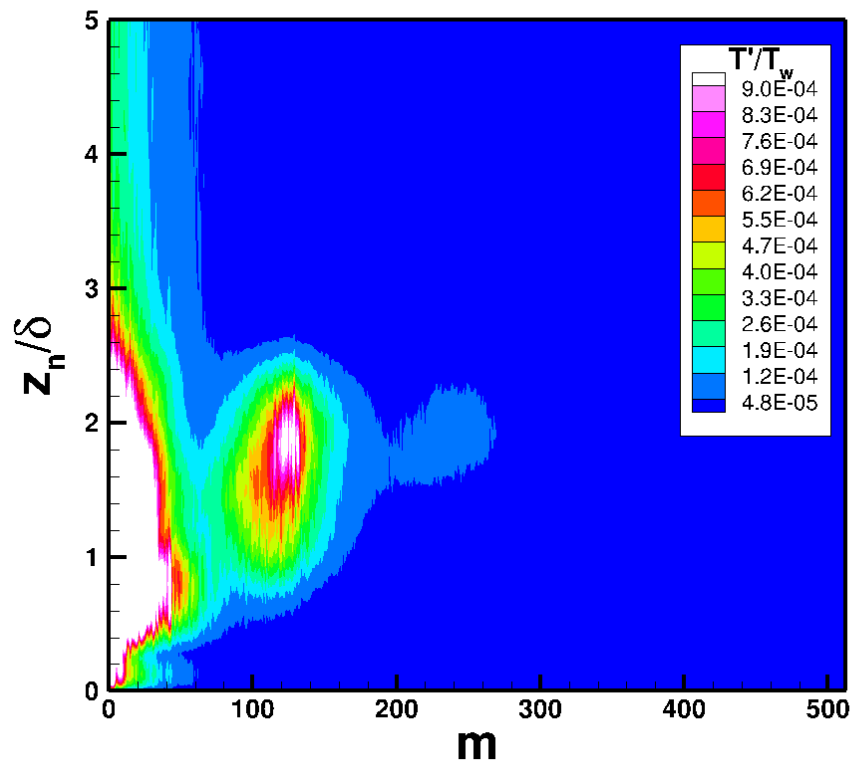
Results: Three-Dimensional DNS of Blunt Cone with Tunnel-Like Acoustic Disturbance

- Power spectral density for wall pressure and heat flux fluctuation
- Formation of the disturbance peak around $f = 168$ kHz
- This peak becomes more evident in downstream locations
- Spatial structures of temperature fluctuation by temporal FFT for a frequency near 167 kHz
- There are strong similarities with the nonmodal analysis for the frequency equal to 150 kHz



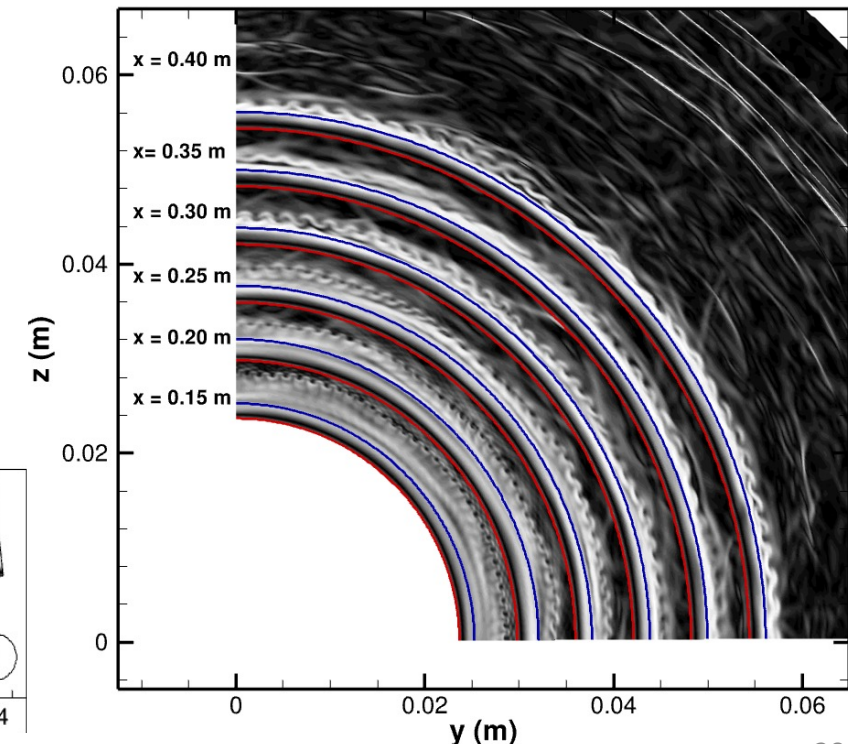
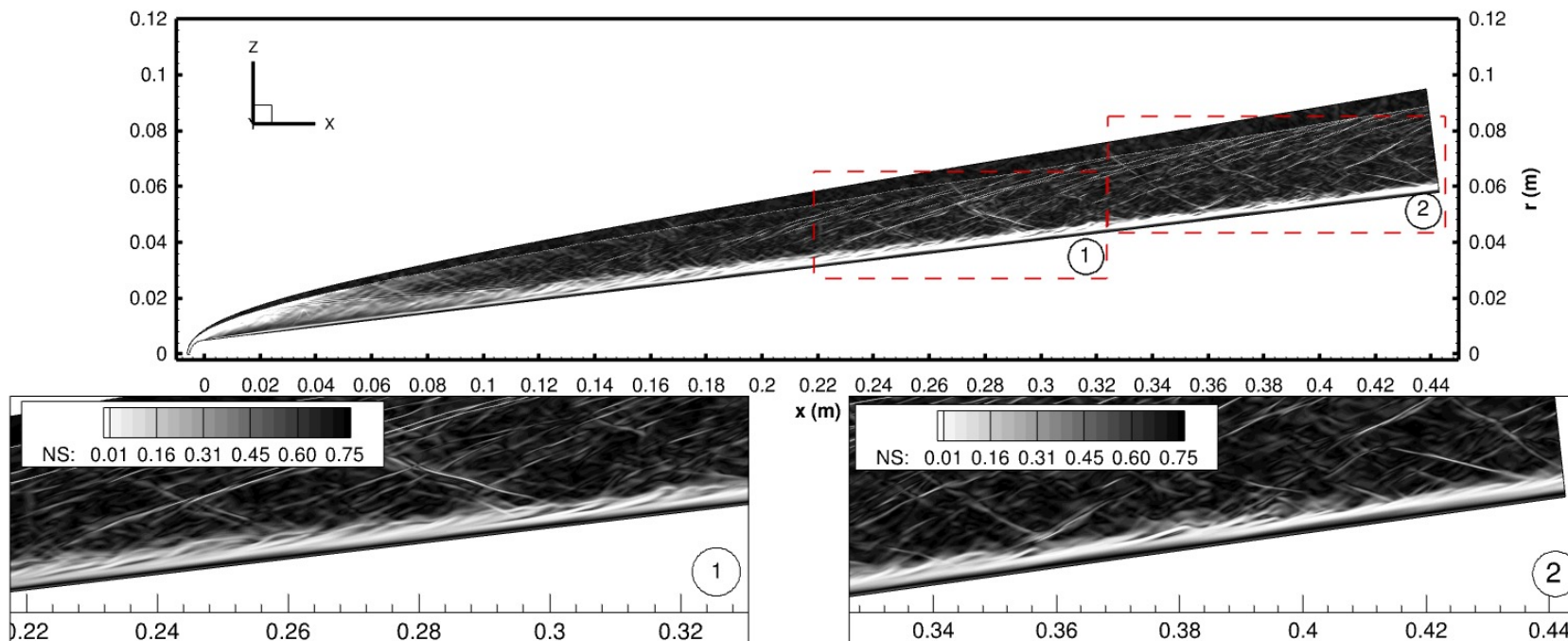
Results: Three-Dimensional DNS of Blunt Cone with Tunnel-Like Acoustic Disturbance

- Wall normal variation in the temperature fluctuation spectra
- Only low azimuthal wavenumber waves penetrate the boundary layer
- There are additional peaks outside the boundary layer involving strongly oblique waves ($m \approx 125$)
- This peak occurs at distances around 2 times the boundary layer thickness
- Super-harmonic of this disturbance is also evident near $m = 250$



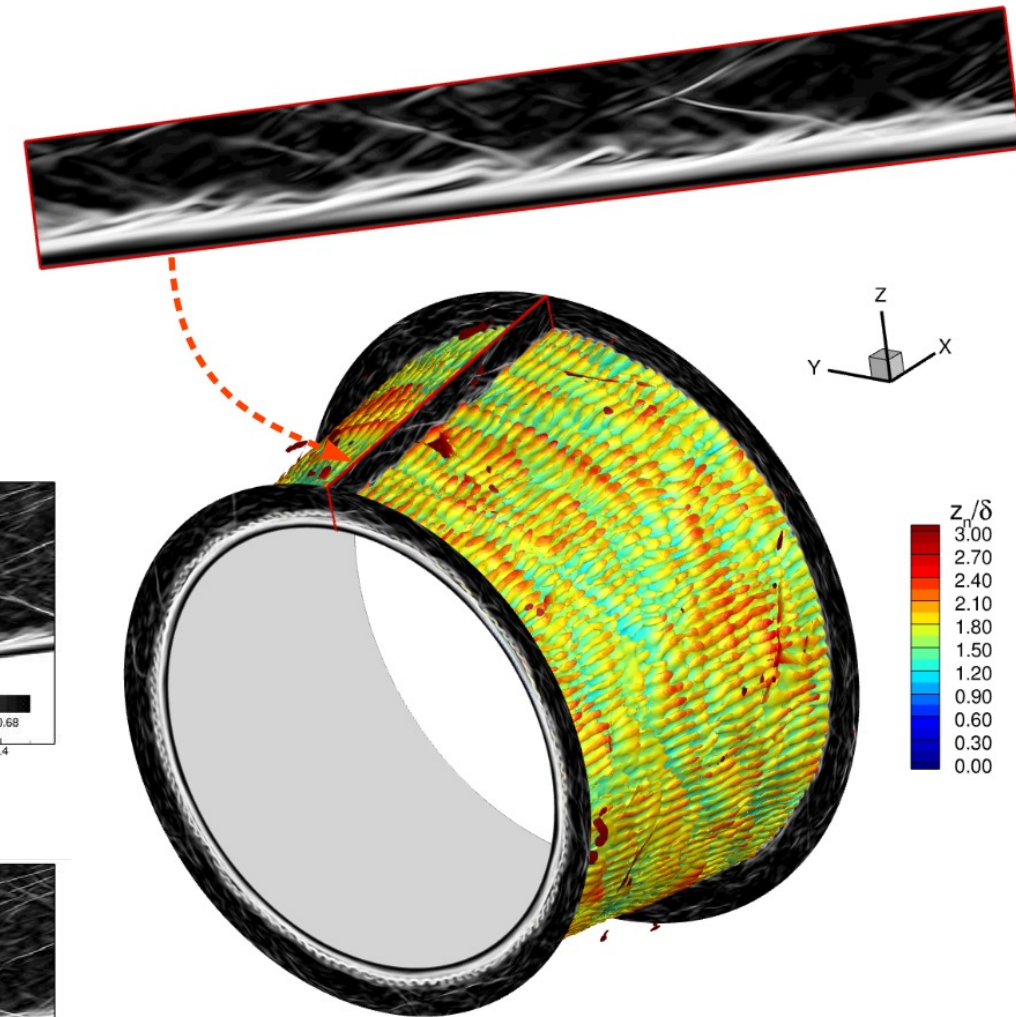
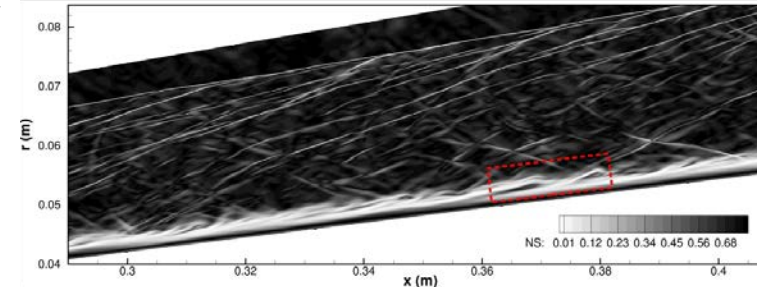
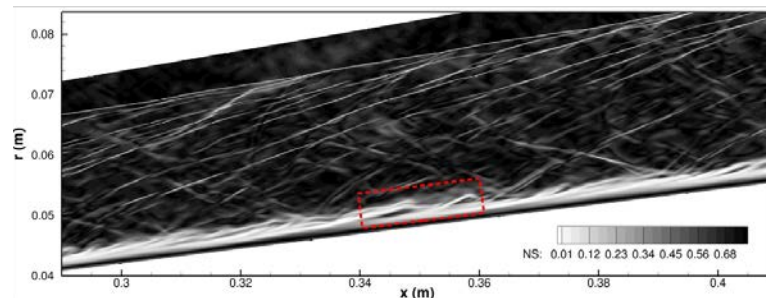
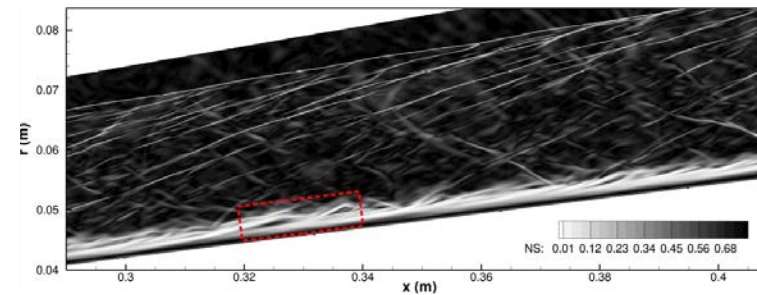
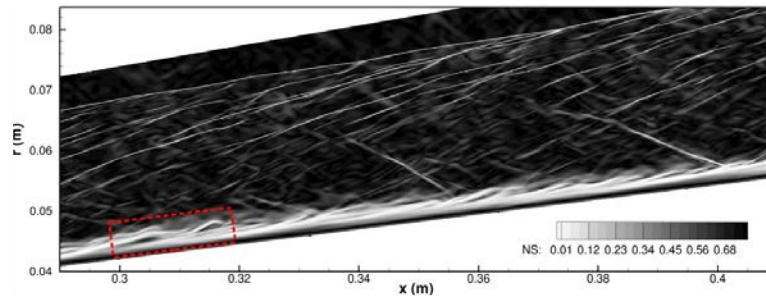
Results: Three-Dimensional DNS of Blunt Cone with Tunnel-Like Acoustic Disturbance

- Numerical schlieren (i.e., density gradient) for axial and transverse planes
- Similar inclined structures are seen in experiments of blunt cones or blunt ogive-cylinder
- Previous research suggested that these disturbances may be associated with nonmodal amplifications
- These inclined structures are initially located farther from the wall
- They approach the boundary layer edge as they travel downstream



Results: Three-Dimensional DNS of Blunt Cone with Tunnel-Like Acoustic Disturbance

- Time evolution of these inclined structures
- The convective speed these structures are around the mean flow speed near the edge of the boundary layer
- These structures remain nearly unchanged as it is convected
- These structures are essentially three dimensional



Summary and Conclusion

- Hypersonic boundary-layer receptivity to a freestream acoustic disturbance was investigated
- The broadband tunnel noise in the freestream of a convectional hypersonic wind tunnel can be well represented by an acoustic model with an ansatz of slow acoustic waves
 - With successful calibration of the model parameters, such an acoustic ansatz can successfully reproduce both the frequency-wavenumber spectra and the temporal evolution of the broadband tunnel noise radiated from the nozzle wall
- The axisymmetric DNS study found that the amplification of Mack's second mode agrees well with the PSE prediction for both sharp and blunt cones
- The spectra of wall-pressure and heat-transfer fluctuations recover the signature of the axisymmetric waves predicted by the nonmodal analysis
- The azimuthal wavenumber and frequency spectrum of the temperature fluctuations as a function of the wall-normal distance show higher amplitudes for three-dimensional waves above the boundary-layer edge
- The numerical Schlieren contours show the inclined structures commonly observed in blunt cone experiments
 - They correspond to 3D structures due to freestream disturbances in the presence of an entropy layer



Acknowledgment

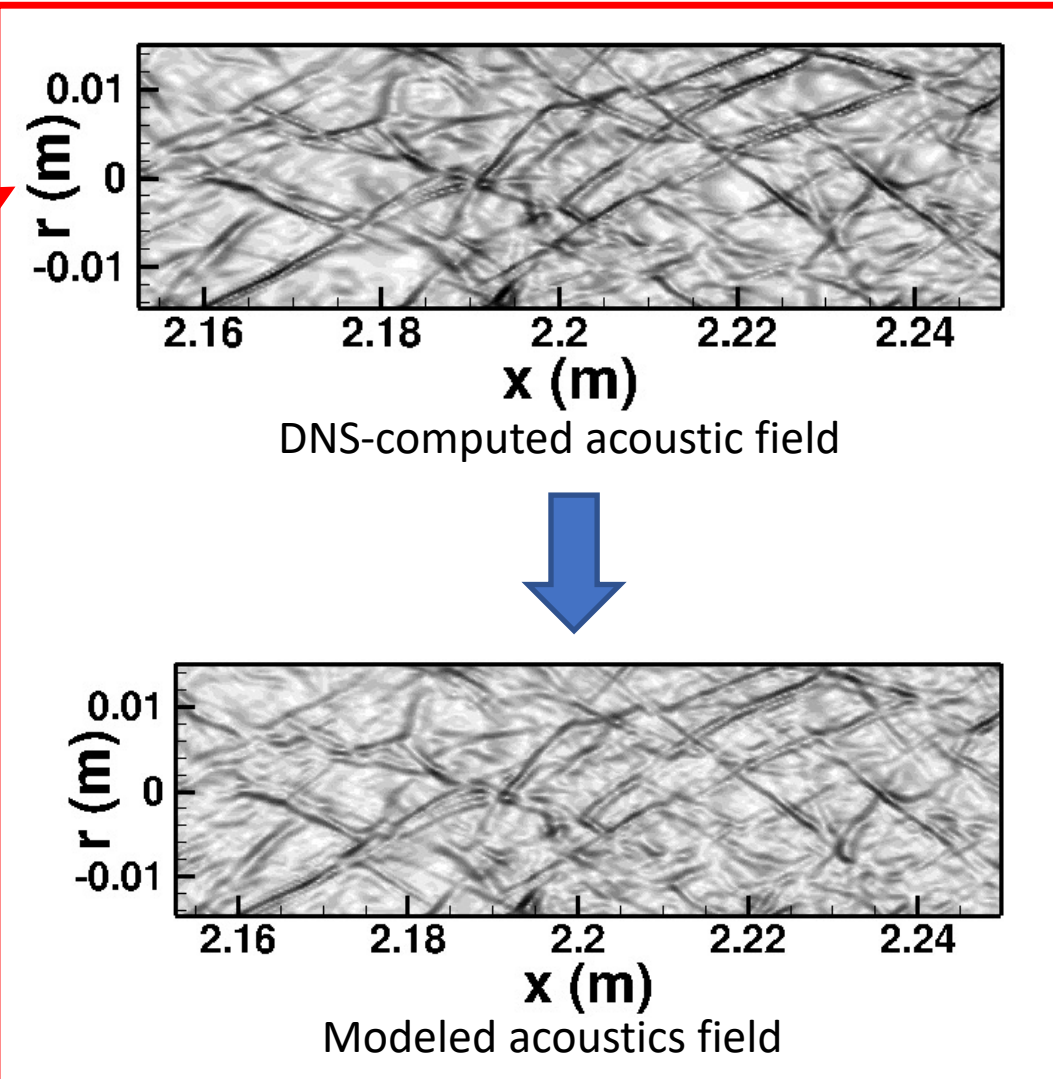
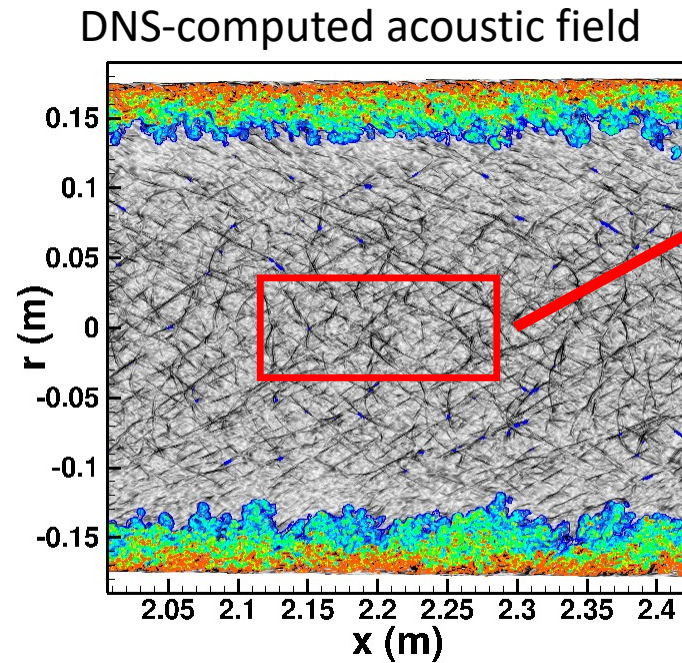


- Financial Support
 - NSF and ONR
- Dr. Katya Casper and Dr. Ross Wagnild of Sandia National Laboratory
 - for their wind-tunnel validation data and many valuable discussions
- Computational resources
 - DoD High Performance Computing Modernization Program
 - Ohio Supercomputer Center



Backup

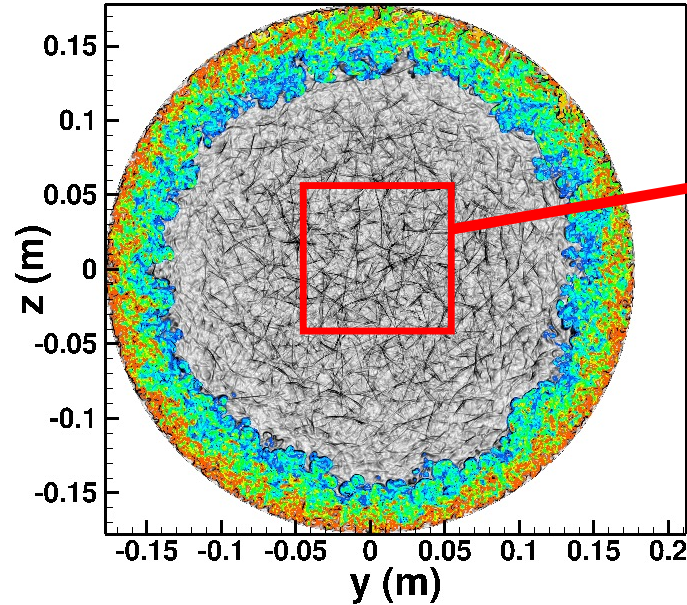
“Tunnel-like” Acoustic Disturbance Generation



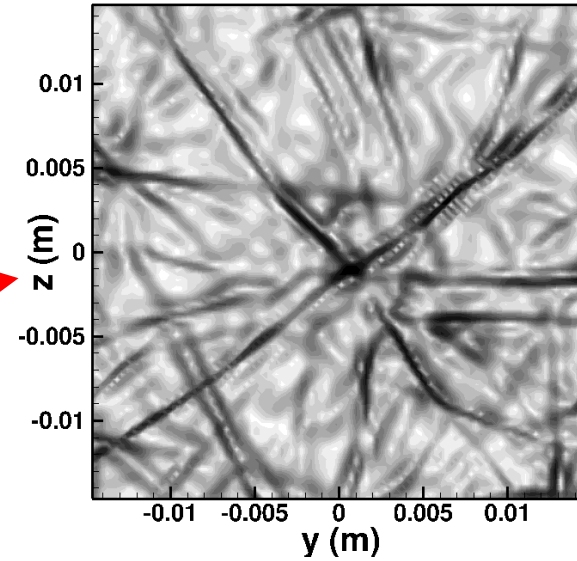
- Instantaneous acoustic structures of the modeled acoustic disturbances matched well with those computed by DNS

“Tunnel-like” acoustic disturbance generation

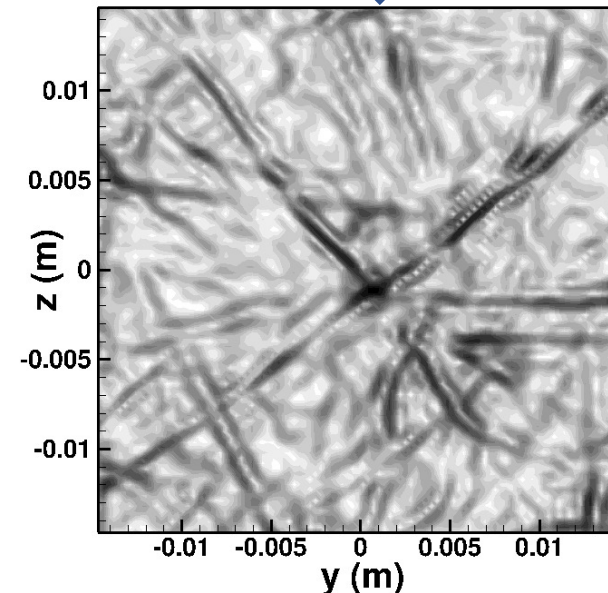
DNS-computed acoustic field



- Instantaneous acoustic structures of the modeled acoustic disturbances matched well with those computed by DNS



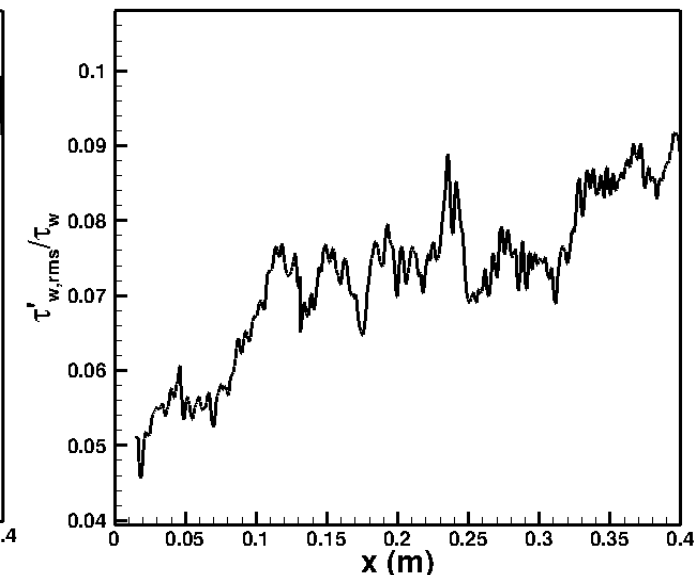
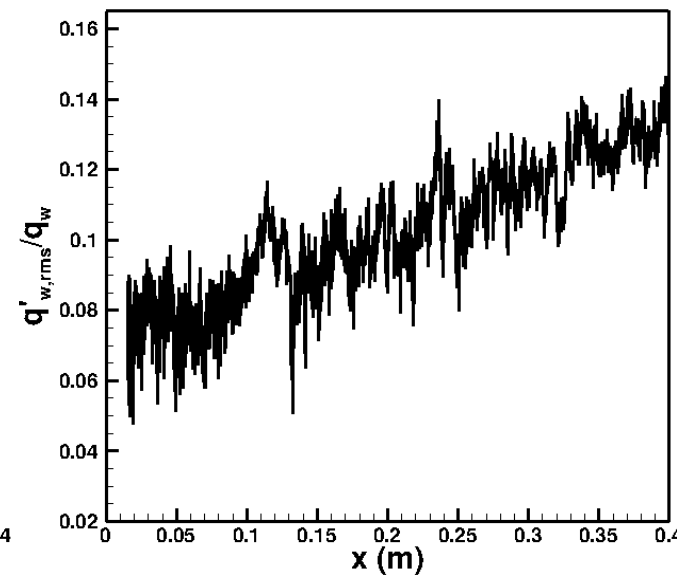
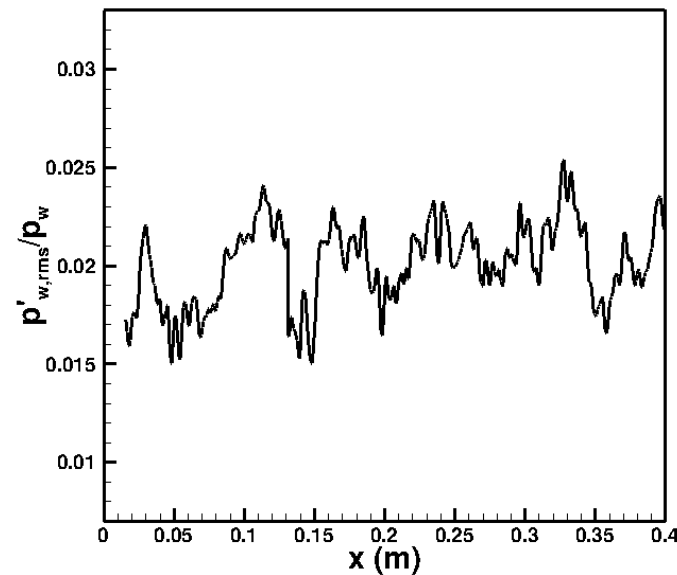
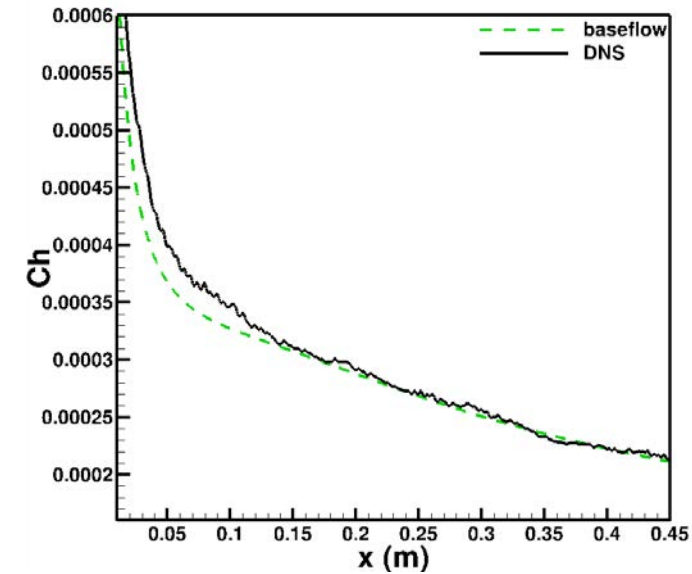
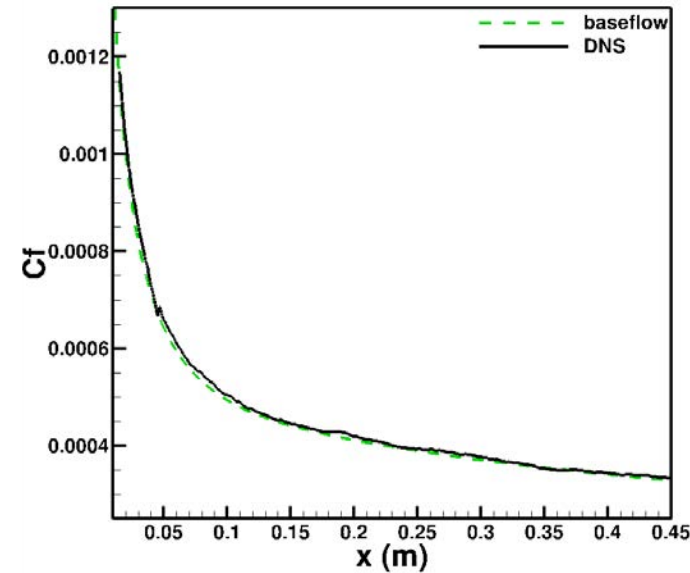
DNS-computed acoustic field



Modeled acoustics field



Results: Three-Dimensional DNS of Blunt Cone with Tunnel-Like Acoustic Disturbance



- Skin-friction coefficient (left)
- Stanton number (right)

- RMS fluctuation:
 - Surface shear stress
 - Wall heat flux
 - Wall pressure