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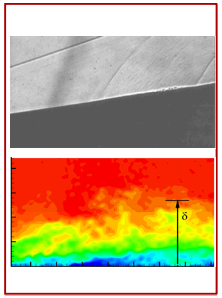

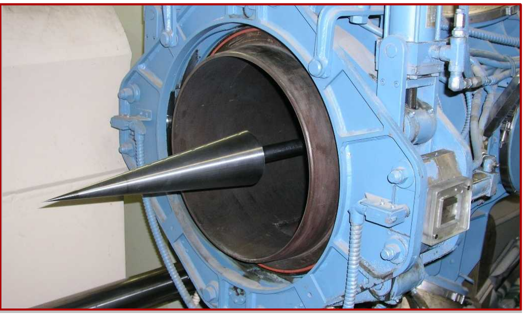

Reentry Random Vibration Research at Sandia National Labs

Presented at Notre Dame FlowPAC Seminar

December 1, 2017

South Bend, IN

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Sandia National Laboratories

Albuquerque, NM

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Outline

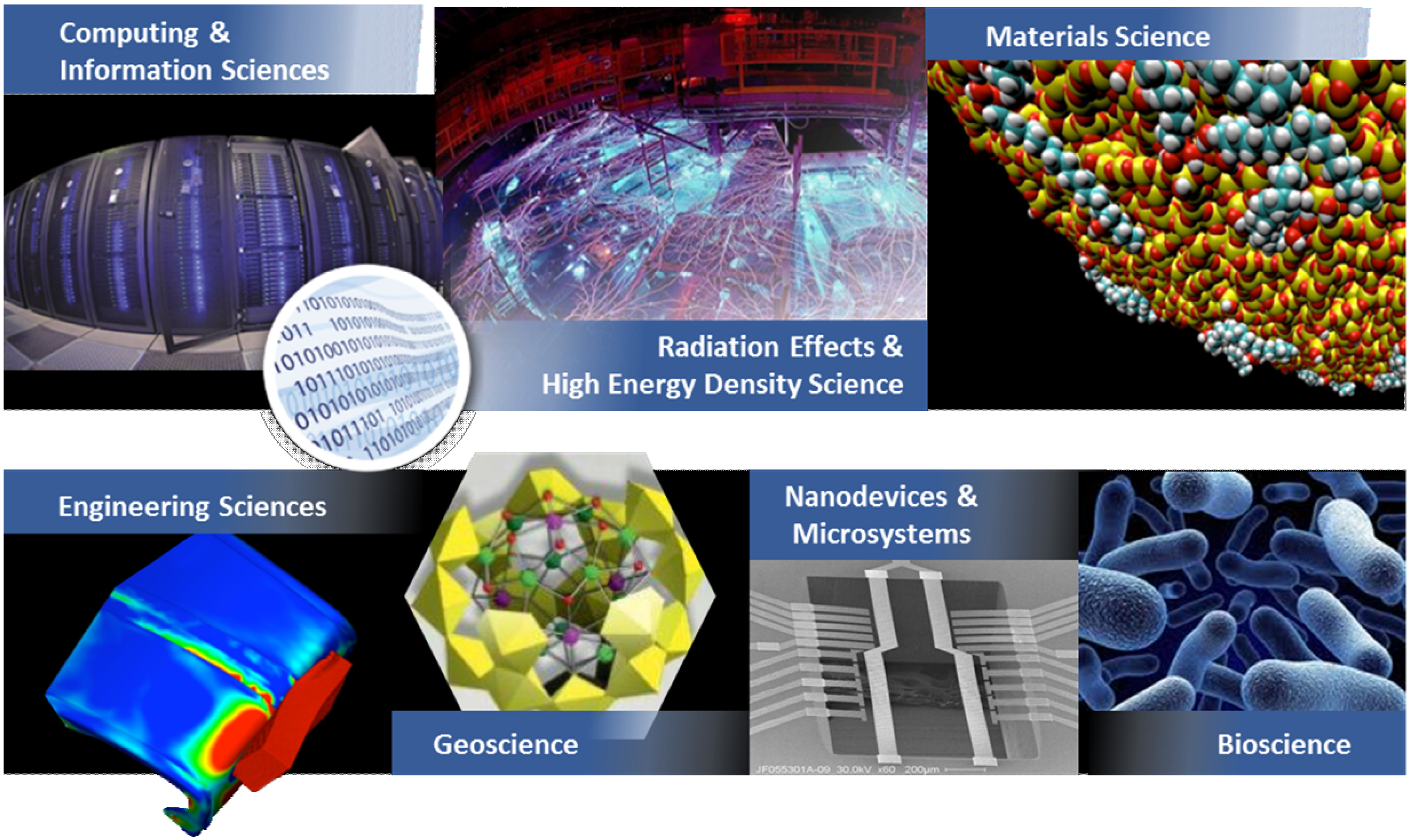
- Aerosciences at Sandia National Labs
- Intro Reentry Random Vibration
  - Turbulent Boundary Layer
  - Transition
- Conclusions
- Future Work

About Sandia

- Sandia has two main locations, but operates at many sites across the country.

Our Foundations in Research

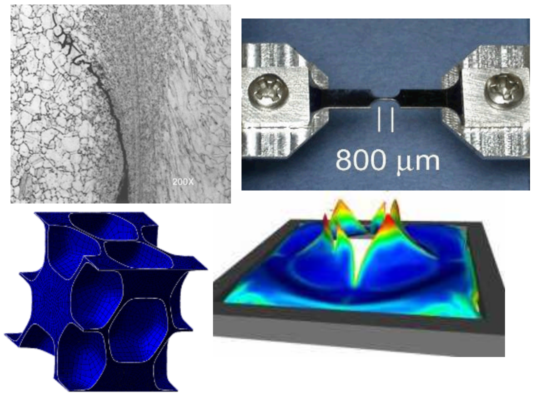
We support essential research-and-discovery activities that translate into invention, innovation, entrepreneurship, economic opportunity, and public benefit.



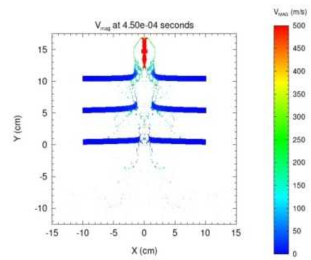
Engineering Sciences Core Technical Areas

Sandia National Laboratories

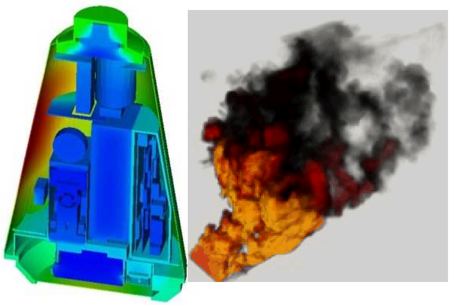
Solid Mechanics



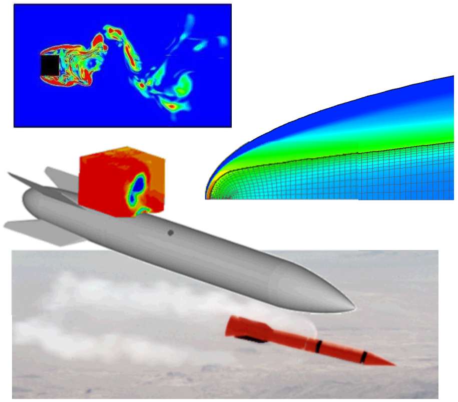
Shock Physics and Energetics



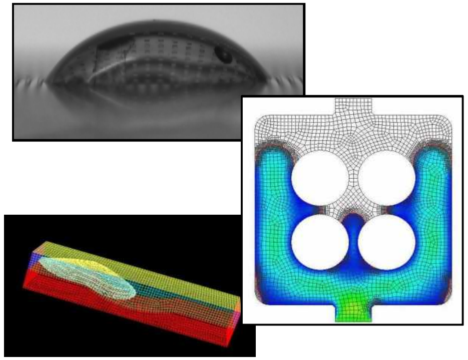
Thermal and Combustion Sciences



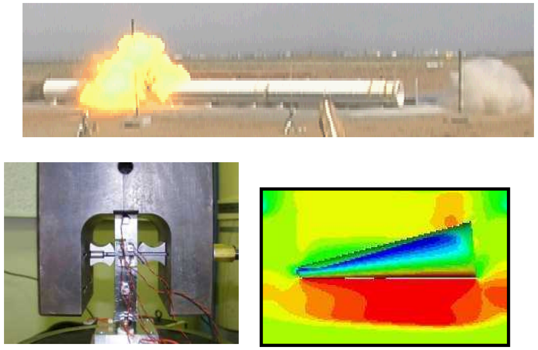
Aerosciences



Fluid Mechanics

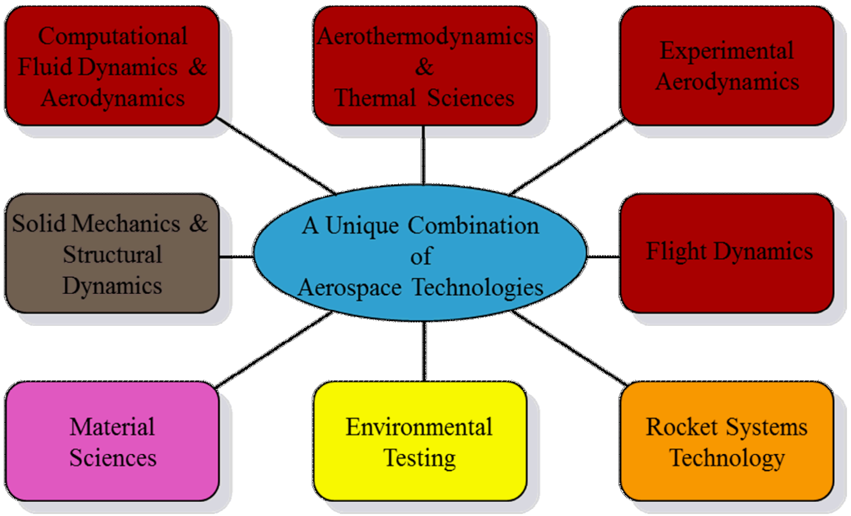


Structural Dynamics



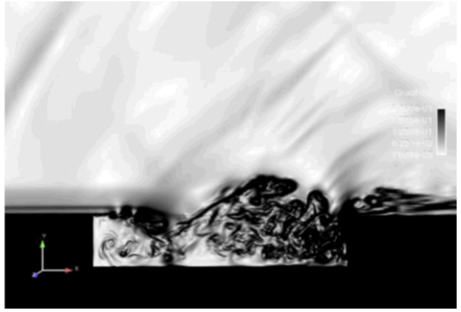
Aerosciences at Sandia

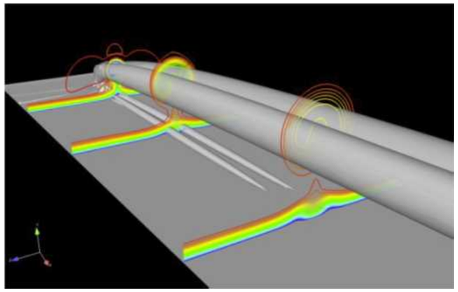
- Only Aero Department in Engineering Sciences
  - 17 Staff spanning all areas
- Expertise
  - Both Computational and Experimental
  - Compressible Flow CFD
    - Numerical Methods, Turbulence Modeling, Software Development
    - Multi-Physics Modeling (FSI, Aero-Thermal Coupling)
    - Models for Re-Entry – Ablation, Random Vibration, Transition, Chemistry
  - Experimental Compressible Flows
    - Advanced Diagnostics – Laser Based, Surface Diagnostics, High Frequency Accels,
    - Experiments for Discovery and Validation
- Activities
  - Balance of Research, Development and Applications
  - Combination of Computations and Experiments - Lab-Scale & Full-scale



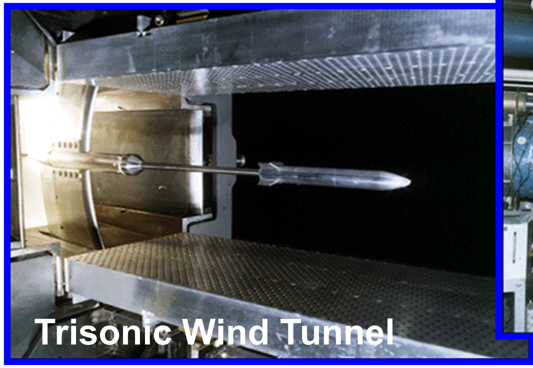
Modeling & Simulation

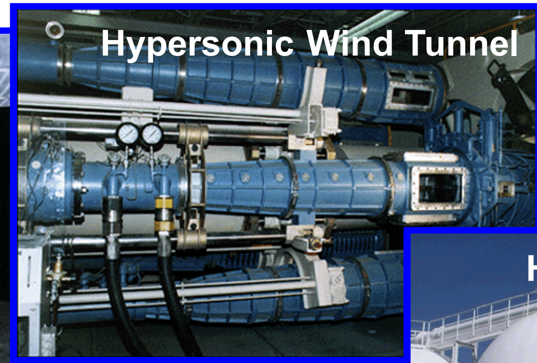
- Applications
  - Engineering simulation activities to Support Surveillance/Modernization Programs
    - Performance Analysis
    - Aerodynamic Model Refinements for Qualification
    - Trajectory/Dispersion Studies
    - Range Safety Analyses
  - Analysis to Define Environments
    - Provide Aero-Induced Vibration Loads
    - Thermal Environment Specifications
    - Multi-Physics applications.
  - Performance through environments
    - Captive Carriage Environments
    - Flight through Ice/Hail/Particle Laden atmosphere





Experimental Aerosciences Facility





- **Trisonic Wind Tunnel (TWT)**
  - Mach 0.5 – 3
  - Gravity bombs, missiles
- **Hypersonic Wind Tunnel (HWT)**
  - Mach 5, 8, 14
  - Re-entry vehicles, rockets
- **High-Altitude Chamber (HAC)**
  - Satellite components
- **Multi-Phase Shock Tube (MST)**
  - Explosives research

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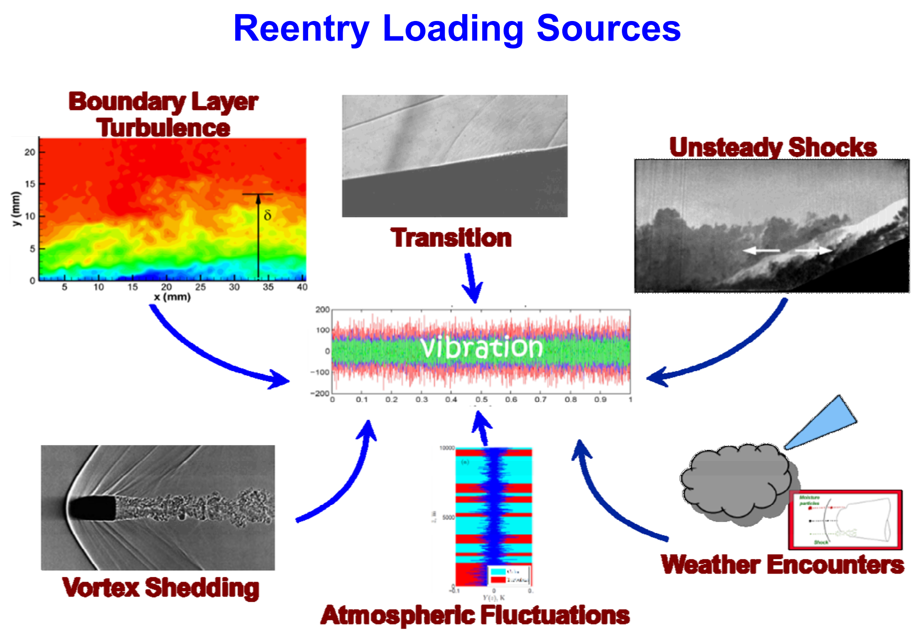
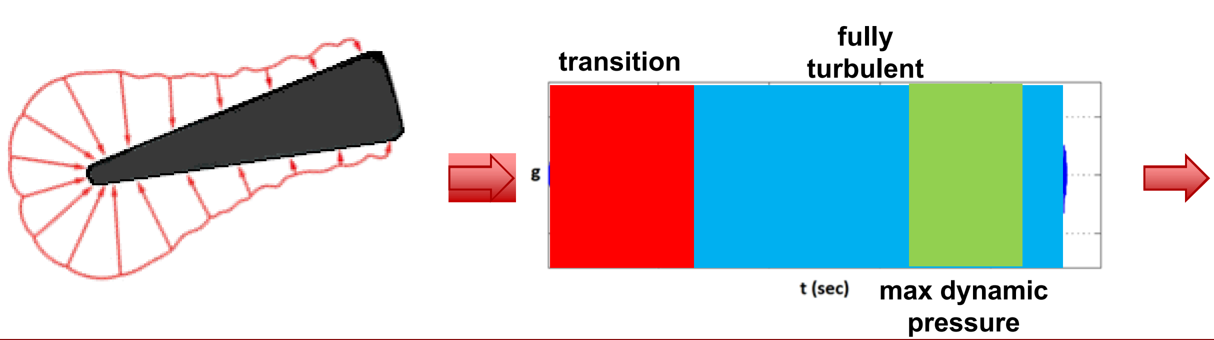
Reentry Vibration Environments

- Reentry Random Vibration
  - Structural response of an RB and internal components
  - Random Aerodynamics Loads
    - Boundary Layer Transition
    - Turbulent Boundary Layer
    - Atmospheric Fluctuations
    - Weather
    - ...



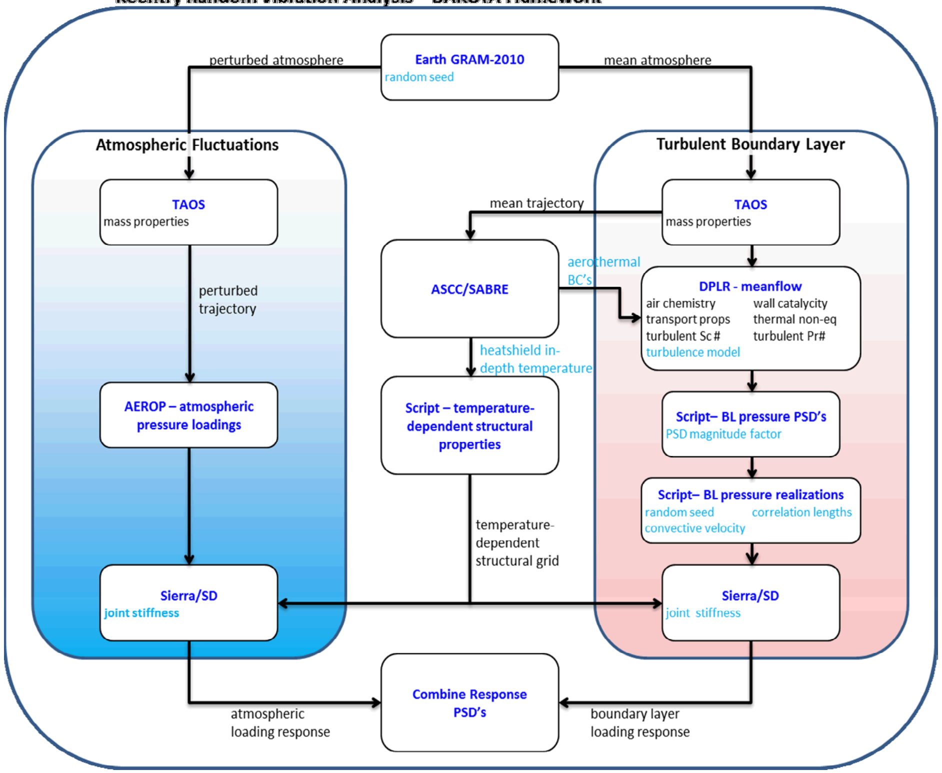


Reentry Vibration Environments

- **Objective:** Develop physics-based simulation capability to assess RV component response during re-entry.

- Turbulent boundary layer loading
  - Driven by pressure/shear fluctuations under a turbulent boundary layer
  - Unsteady fluid flow problem with a range of length scales
  - Too expensive to model directly (scales as ~Re^3)
  - Modeled using a statistical approach defined by a random pressure field
    - Define: ASD, CSD, PDF
  - Supported by ground test data
- Atmospheric loading
  - Driven by atmospheric fluctuations (density, pressure, temperature, wind)
  - Influences low-frequency response
  - Modeled phenomenologically
- Bundled in Dakota Framework for UQ studies and to improve efficiency to solution

Reentry Random Vibration Analysis – DAKOTA Framework



Pressure Auto Spectral Density

- The asd describes the magnitude of fluctuations vs. frequency
  - Theoretical model for the asd derived by DeChant[*]

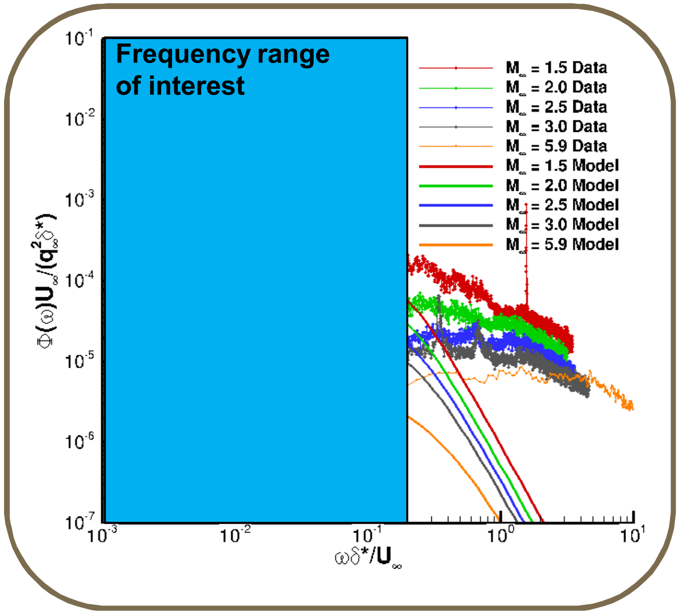
$$\Phi = \frac{(4\tau_{wall})^2\delta}{U_\infty}\left[\underbrace{\frac{\omega}{(1+\omega^2)(\alpha^2\omega^2+1)^2}}_{\text{near wall, low speed}} + \underbrace{\beta\exp(-\sqrt{\alpha\pi}\omega)}_{\text{farfield, compressible, low frequency}}\right]$$

near wall, low speed

farfield, compressible, low frequency

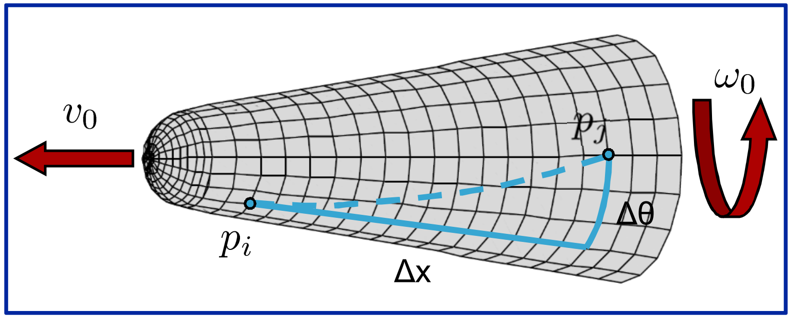
$$\omega = 2\pi f\frac{\delta}{U_\infty};\ \ \alpha = \sqrt{M_\infty^2 - 1};\ \ \beta = \Phi_{near\ wall\ max}$$

- Results compare well to wind tunnel data of Beresh & Casper
  - Fair agreement at lower frequencies, roll-off not captured correctly



[*]L. J. DeChant and J. A. Smith, “An Approximate Turbulent Pressure Fluctuation Frequency Spectra for a Finite Supersonic Plate,” AIAA Paper 2015-1985, Presented at the 53rd AIAA Aerospace Sciences Meeting, Kissimmee, FL, January 2015.

Cross Spectral Density



- Historically, the aerodynamics community has used the Corcos cross spectral density to describe the relation of pressure at one point on a body to another:

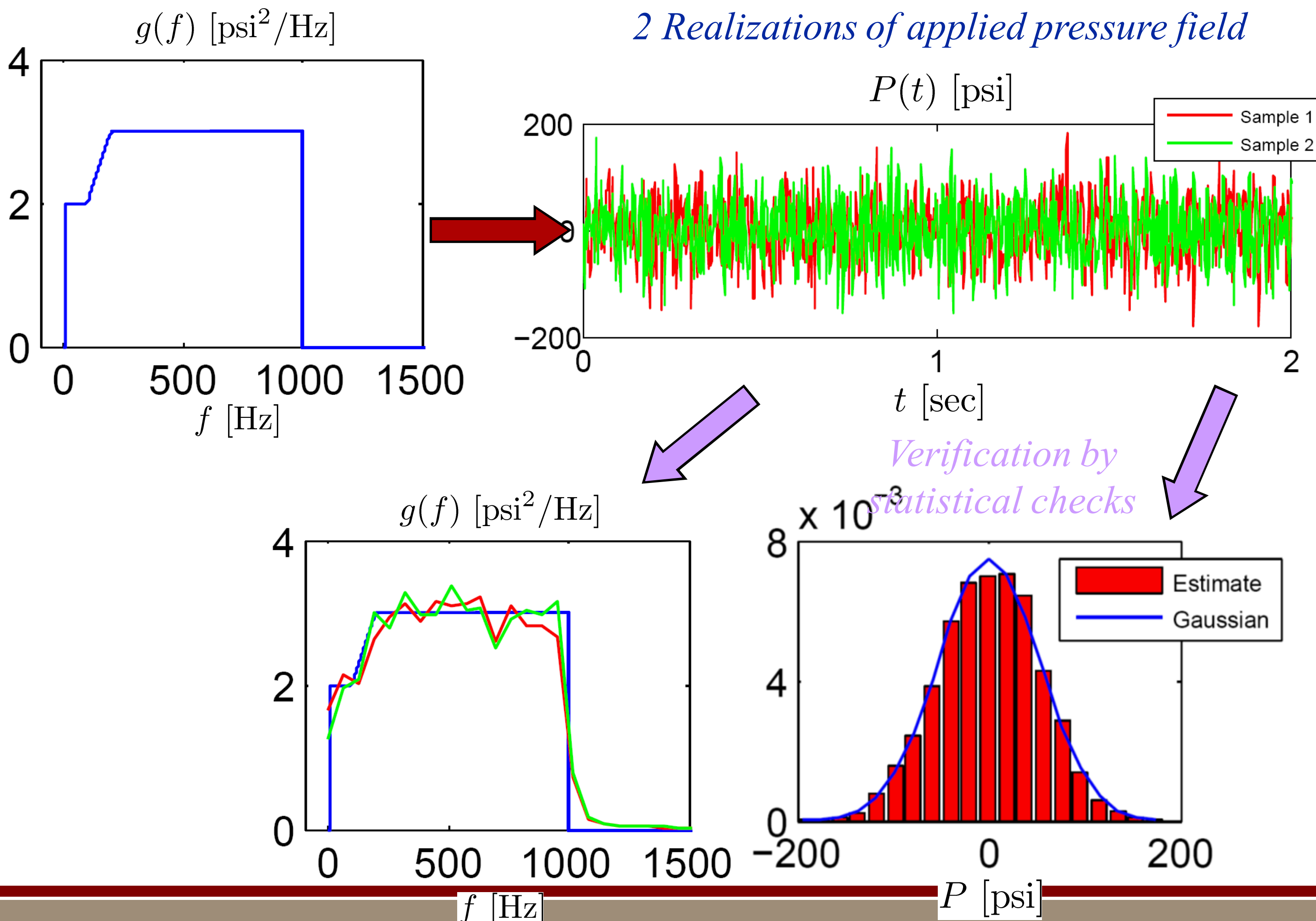
$$\boldsymbol{\Gamma}(\boldsymbol{\omega}, \Delta \boldsymbol{x}, \Delta \boldsymbol{\theta}) = \boldsymbol{\Phi}(\boldsymbol{\omega}) \exp\left(-i \frac{\boldsymbol{\omega} \Delta \tilde{\boldsymbol{x}}}{\boldsymbol{U}}\right) \exp\left(-\boldsymbol{\alpha} \frac{\boldsymbol{\omega} \Delta \tilde{\boldsymbol{x}}}{\boldsymbol{U}}\right) \exp\left(-\boldsymbol{\beta} \frac{\boldsymbol{\omega} \bar{\boldsymbol{r}} \Delta \tilde{\boldsymbol{\theta}}}{\boldsymbol{U}}\right)$$

- Corcos decay parameters have been fit using classical zero pressure gradient low speed/incompressible datasets.
  - α = 0.11: exponential decay parameter in the axial direction
  - β = 0.38: exponential decay parameter in the lateral direction
- The higher speed flowfields/boundary layers in hypersonic flight are expected to exhibit qualitatively different behavior because of compressibility effects
  - Fits to compressible data sets from Mach 1.5 to 3.0 have yielded new decay constants:
  - α = 0.36, β = 0.70

Pressure Realizations

Time Realizations of Fully Developed Boundary Layer Pressure Loading

Input ASD (from Aero analysis)

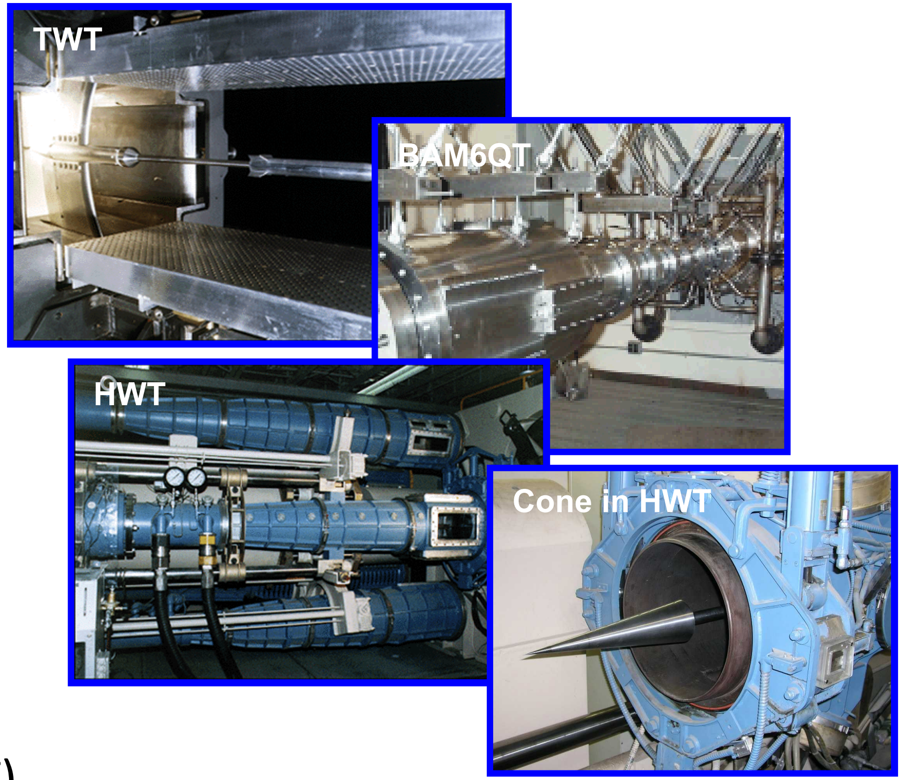


UQ / V&V Challenges

- We compare to flight test data for model validation and calibration, but those data are limited in scope
  - Surface pressures are not measured, only component response
  - Flight data uncertainty is difficult to characterize (lack of repeat flight tests)
  - Flight test data uncertainty cannot be attributed to individual phenomena
- We also rely on ground test data for model validation
  - Controlled experiments
  - Measure load and response
  - Missing some of the physics of reentry
- Modeling Uncertainty:
  - Atmosphere, trajectory
  - Heatshield response, ablation (temperature, blowing, shape)
  - ASD and spatial correlation form and scale
  - CFD turbulence model

Experimental Setup

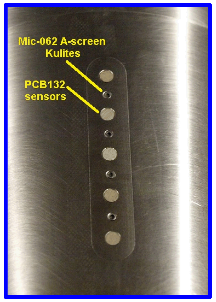
- Sandia Trisonic Wind Tunnel (TWT)
  - Blowdown to atmosphere
  - M_∞ = 0.5-1.3, 1.5, 2.0, 2.5, 3.0
  - Re = 10–66 x 10^6 /m
  - 305mm x 305mm (1’x1’) test section
- Purdue BAM6QT
  - Ludwieg Tube
  - M_∞ = 6
  - Re = 0.4-18.3 x 10^6 /m
  - 459 mm diameter (18 in.) test section
- Sandia Hypersonic Wind Tunnel (HWT)
  - Blowdown to vacuum
  - M_∞ = 5, 8, 14
  - Re = 0.7–32.8 x 10^6 /m
  - 459 mm diameter (18 in.) test section

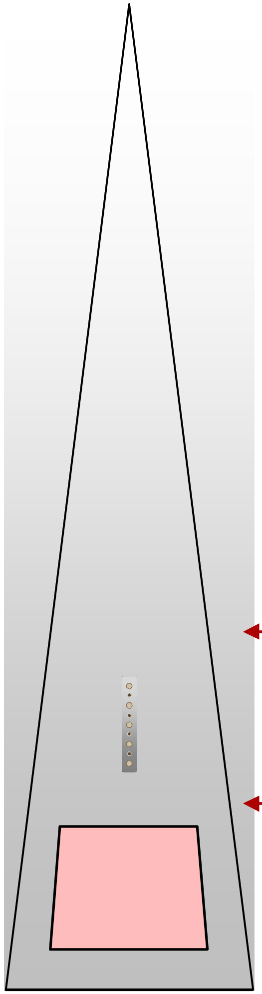


Geometry	M_∞	Re (10^6/m)	P_0 (kPa)	T_0 (K)	M_e	U_e (m/s)	q_e (kPa)	δ (mm)	δ^* (mm)	τ_w (Pa)
Wall	1.5	27.8	223.8	320	1.5	442	91.0	16.0	2.5	164
Wall	2.0	35.6	338.6	330	2.0	532	117.0	14.0	2.8	187
Wall	2.5	35.7	432.5	330	2.5	600	108.0	14.8	3.6	162
Wall	3.0	30.6	480.5	320	3.0	649	81.3	16.8	4.8	102
Wall	5.9	10.6	941.3	430	5.9	870	16.2	24.4	13.1	86
Wall	7.9	9.4	3411.3	630	7.9	1097	17.0	35.4	20.1	138
Cone	5.0	15.9	900.4	400	4.0	784	34.4	2.5	1.1	59
Cone	7.9	13.4	4692.2	620	6.3	1068	38.8	2.9	1.5	46

Experimental Setup

- HWT Cone wind tunnel tests conducted at Sandia by Casper
  - 7° half-angle cone, 0.517 m long
  - Axial insert of pressure sensors; 0.355 m ≤ x ≤ 0.396 m
  - Spanwise insert of PCB132 sensors; x=0.452 m
  - Schlieren view of boundary layer; 0.326 m ≤ x ≤ 0.416 m
  - Mic-062 Kulite pressure sensors
    - frequency ~ 0:50 kHz
  - PCB132 pressure sensors
    - frequency ~ 11 kHz : 1 MHz
    - sensor diameter = 3.2 mm
    - "sensitive diameter" 1.43 mm
  - Thin panel with attached accelerometers
    - composite or steel; with and without weights





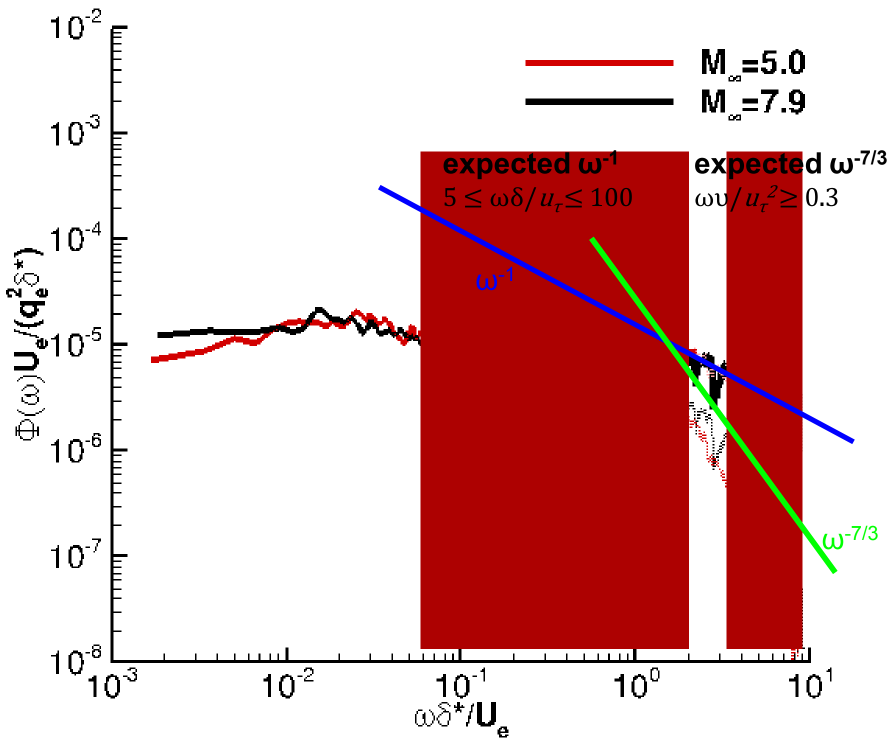
Schlieren viewing area

Experimental Data

- HWT Cone Pressure Spectra
  - Dimensional Signal
  - Non-dimensionalized
  - Corcos-Correction
    - Sensor spatial attenuation

      $$\Phi' = \Phi \cdot \exp(0.876\omega_D r/U_c)$$

    - Applicability at high frequencies is questionable (Schewe*), i.e. when $\omega_D r/U_c \geq 4$.
  - Expected rolloff behavior
    - log layer ~ω^{-1}
    - intermediate regime ~$\omega^{-7/3}$

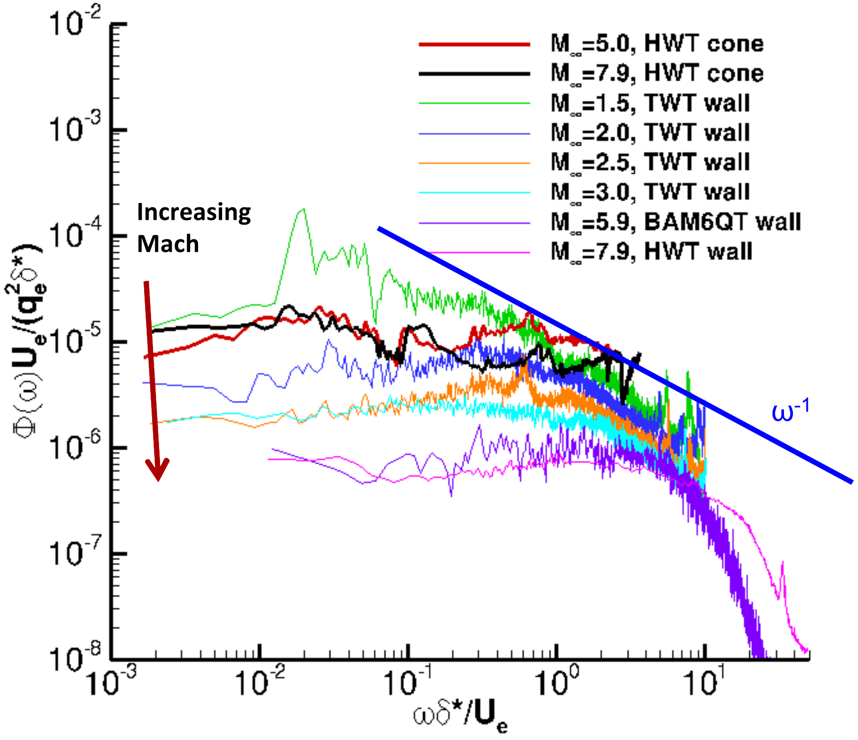


*Schewe, G., "On the structure and resolution of wall-pressure fluctuations associated with turbulent boundary-layer flow," *J. Fluid Mec.* Vol. 134, 1983, pp. 311-328.

Experimental Data

- HWT Cone Pressure Spectra
- Add TWT Wall
  - Exhibit expected ω^{-1} rolloff
- Add BAM6QT Wall
- Add HWT Wall

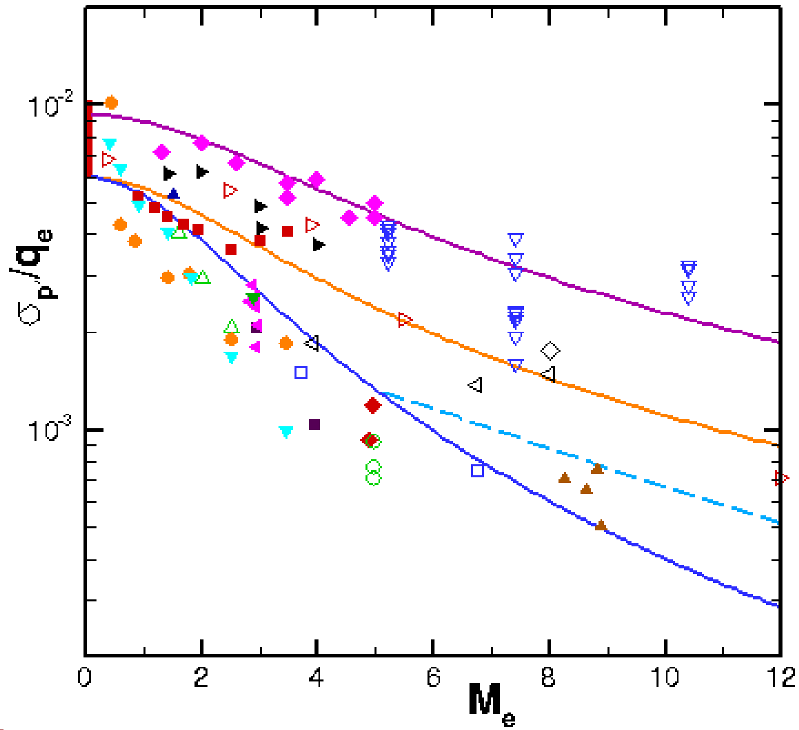
- PSD magnitude decreases with increasing Mach number
  - HWT Cone data are inconsistent with the wind tunnel wall data trend



Experimental Data

- We integrate the spectra to determine the rms pressure, $\sigma_{p'} = \sqrt{\int_0^\infty \Phi(f)\mathrm{d}f}$
  - We have truncated all curves to 300 kHz for consistency

Geometry	M_∞	q_e (kPa)	τ_w (Pa)	σ_p'/q_e (Corcos)	σ_p'/q_e (no-Corcos)
Wall	1.5	91.0	164	0.0064	-
Wall	2.0	117.0	187	0.0048	-
Wall	2.5	108.0	162	0.0039	-
Wall	3.0	81.3	102	0.0034	-
Wall	5.9	16.2	86	0.0028	-
Wall	7.9	17.0	138	0.0030	0.0026
Cone	5.0	34.4	59	0.0170	0.0036
Cone	7.9	38.8	46	0.0144	0.0033



Theory (Improved ASD Model)

- The pressure auto spectral density relationship approximately solves a non-homogeneous wave equation of the form:

$$(M_\infty^2 - 1)\frac{\partial^2 \rho'}{\partial x^2} - \frac{\partial^2 \rho'}{\partial y^2} = \frac{\rho}{a_0^2}\left(\frac{\partial v'}{\partial x}\right)\left(\frac{\partial u}{\partial y}\right)$$

with an approximate relation for the source term, $S(x,y) = \frac{\rho}{a_0^2}\left(\frac{\partial v'}{\partial x}\right)\left(\frac{\partial u}{\partial y}\right) \propto \frac{y}{L}\exp\left(-10\frac{y}{L} - \frac{x}{L}\right)$, which captures the mean-turbulent fluctuation interaction term

- Our previous solution to the above wave equation* yielded a "low speed" model:

$$\Phi = \frac{(4\tau_{wall})^2\delta}{U_e}\left[\frac{\omega}{(1+\omega^2)\left(\alpha^2\omega^2 + {\delta_0}^2\right)^2} + \beta\exp\left(-\sqrt{\frac{\alpha}{\delta_0}}\alpha_0\omega\right)\right]$$

near wall, low speed (first term)

farfield, compressible, low frequency (second term)

- This relationship includes a functional form meant to capture the near wall, high-frequency portion of the spectrum and the farfield, low-frequency behavior

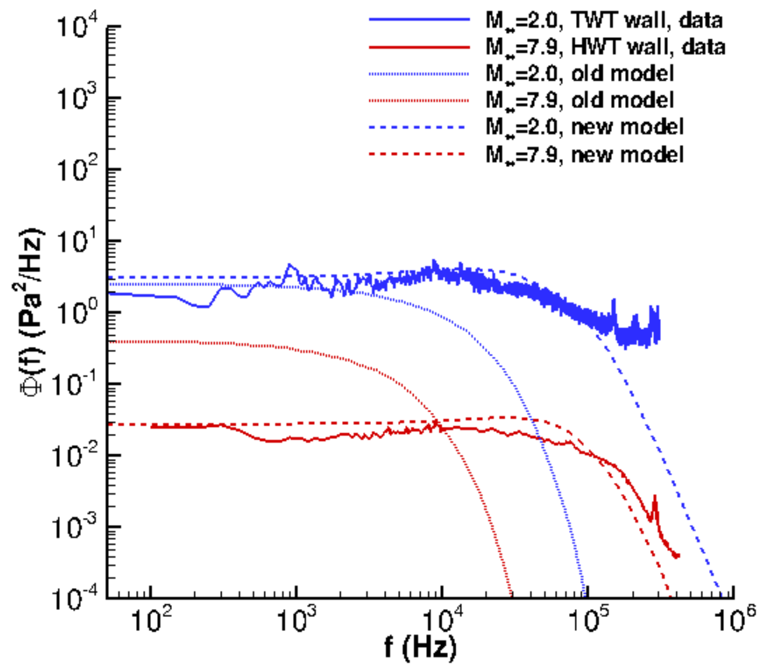
*L. J. DeChant and J. A. Smith, "An Approximate Turbulent Pressure Fluctuation Frequency Spectra for a Finite Supersonic Plate," AIAA Paper 2015-1985, Presented at the 53rd AIAA Aerospace Sciences Meeting, Kissimmee, FL, January 2015.

Theory (Improved ASD Model)

- The "low speed" model captures the experimentally-observed flat portion of the spectrum, but rolls off much too quickly.
- To improve the roll-off behavior, we make compressible scaling arguments and some empiricism (described in the paper) to yield a better-fitting high-speed model:

$$\Phi = \frac{(4\tau_{wall})^2 \delta}{U_e (M_e - 1)^2} \left[\frac{\pi \delta_0^3 \widehat{\omega}}{(1+\widehat{\omega}^2)(\alpha^2 \widehat{\omega}^2 + \delta_0^2)^2} + \beta \exp\left(-\sqrt{\frac{\alpha}{\delta_0} \alpha_0 \widehat{\omega}} \right) \right]$$

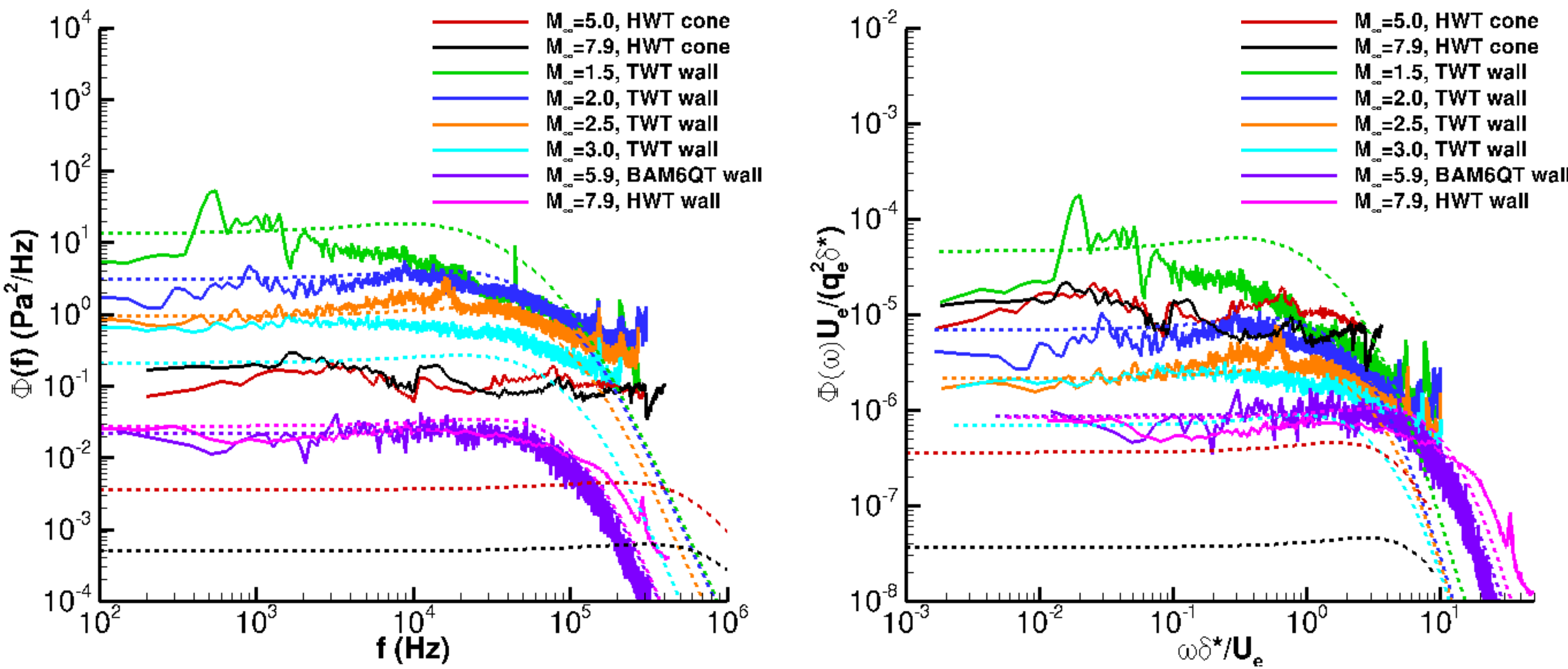
- τ_{wall} = wall shear stress
  δ = boundary layer thickness
  U_e = edge velocity
  M_e = edge Mach number
  $\alpha = \left(M_e{}^2 - 1\right)^{1/2}$
  $\delta_0 = \frac{L}{\delta} \sim 10$
  α_0 = 2.345
  $\widehat{\omega} = \frac{\omega}{2M_e} = \frac{1}{2M_e} \frac{2\pi f \delta}{U_e}$



Comparison of Theory and Experiment

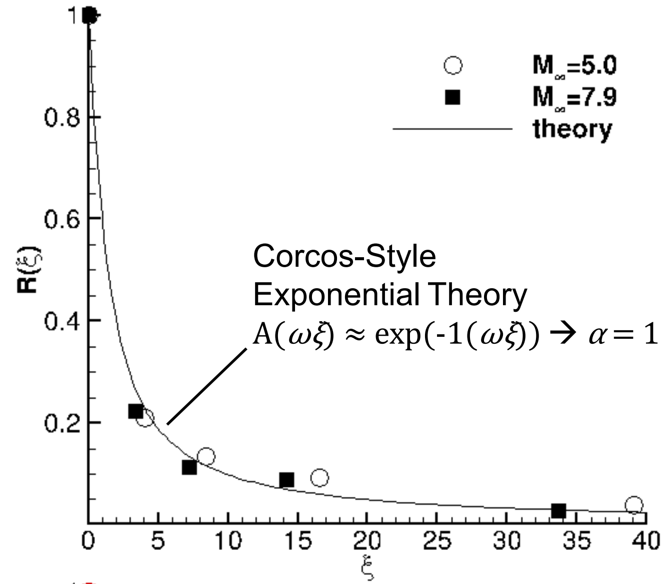
- We now compare the measured pressure spectra with our theory:

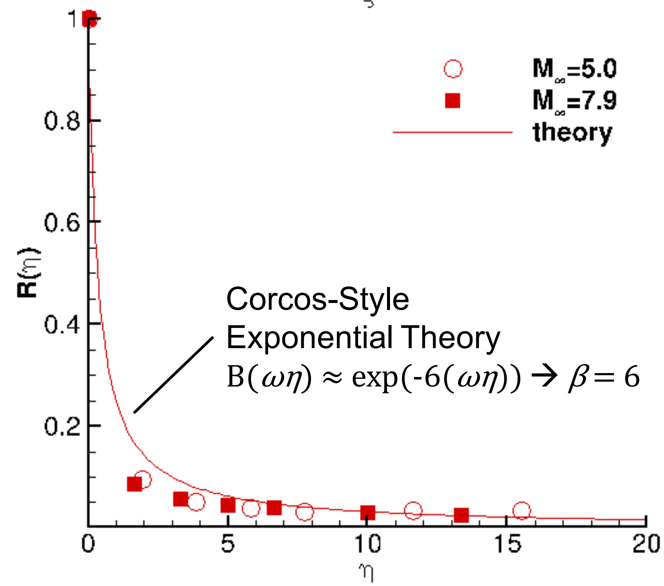
$$\Phi = \frac{(4\tau_{wall})^2\delta}{U_e(M_e-1)^2}\left[\frac{\pi\delta_0^3\hat{\omega}}{(1+\hat{\omega}^2)(\alpha^2\hat{\omega}^2+\delta_0^2)^2}+\beta\exp\left(-\sqrt{\frac{\alpha}{\delta_0}}\alpha_0\hat{\omega}\right)\right]$$



Comparison of Theory and Experiment

- We utilize the HWT cone data to provide correlation functions across our sensor arrays:
  - Classical incompressible values:
    - $\alpha = 0.11, \beta = 0.38$
  - Supersonic (TWT) compressible values:
    - $\alpha = 0.36, \beta = 0.7$
  - HWT cone decay constants are **very high**, suggesting less correlation
    - We are currently reviewing our methods and plan to generalize our analysis to remove simplifying assumptions





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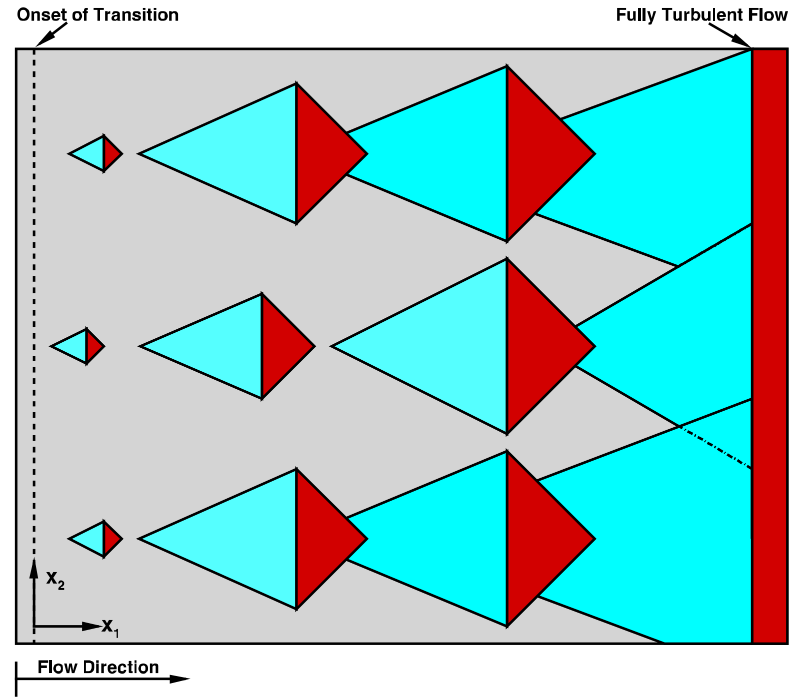
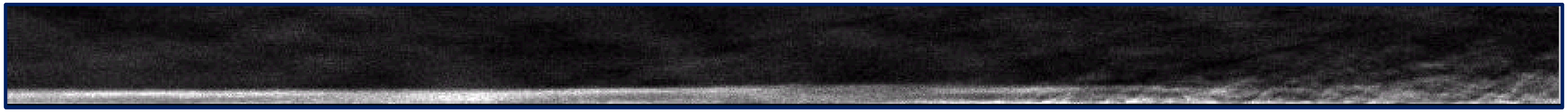
Characterizing Pressure Loading on Relevant Geometries

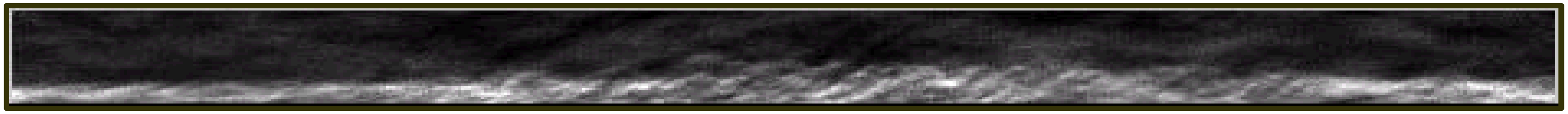


Initial work focused on developing more accurate models of the pressure fluctuations using a turbulent-spot approach.

- At low speeds, the boundary layer switches between smooth laminar flow and turbulence.
  - Characterized by intermittency, burst rate, and average burst length at a given point.
- At hypersonic Mach numbers, second-mode waves are important and occur at the same time as turbulent spots during the transitional region.



Transitional Boundary Layer, Mach 5



Transitional Boundary Layer, Mach 8

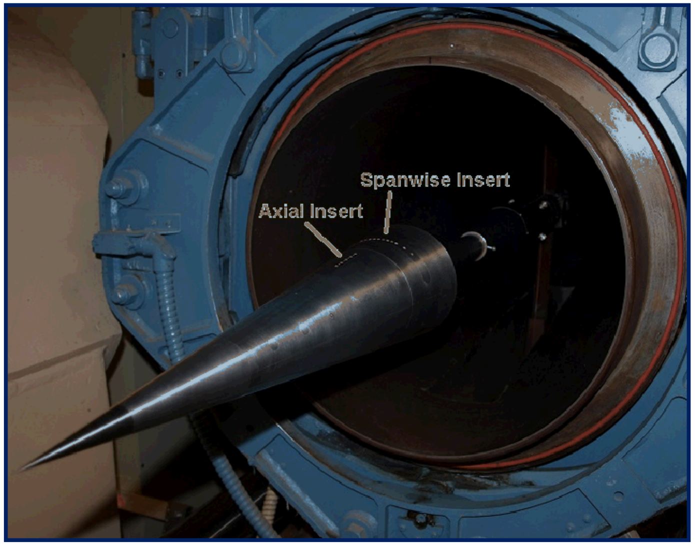
Experimental Setup

We want to study natural transitional boundary layers on a cone at Mach 5 and 8 to obtain transitional statistics.

- Simultaneous schlieren imaging and high-frequency pressure measurements.

Seven degree stainless-steel sharp cone in Sandia's Hypersonic Wind Tunnel.

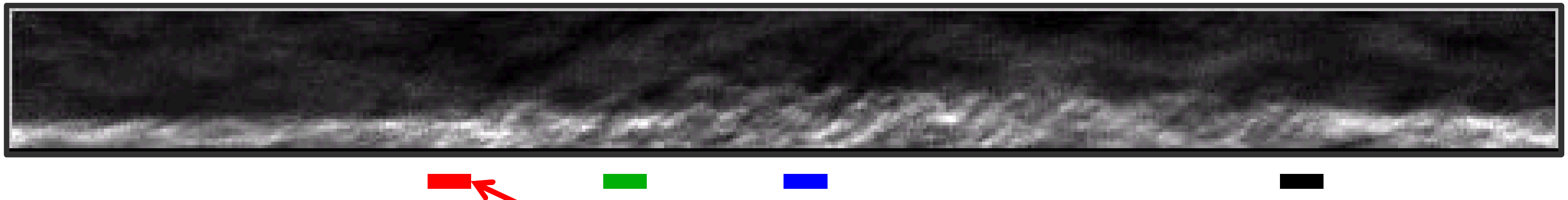
- Axial array with closely spaced high-frequency pressure transducers.
- Directly beneath schlieren viewing area.



Model installed in HWT.

Axial pressure-transducer array.

Computation of Boundary-Layer Statistics, Mach 8, Re = 9.74 x 10^6/m



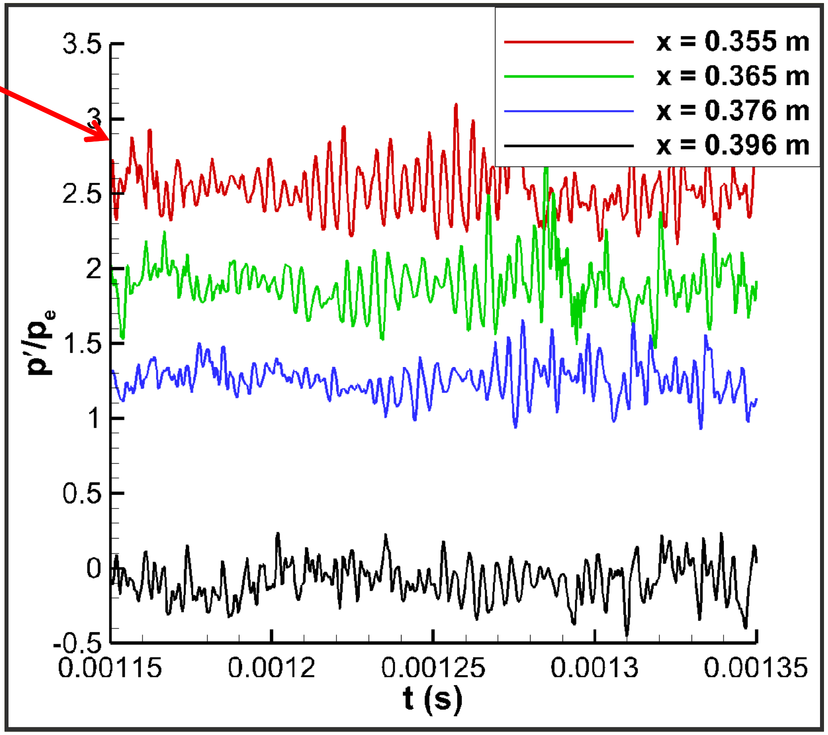
Schlieren Videos

Flow alternates between second-mode waves and turbulence.

- Smooth, laminar boundary layer not observed in transitional region.

Important to separate waves from turbulence in this case.

- Wavelet transform technique developed to do this.
- Once separated, we can compute boundary-layer intermittency and burst rates for waves and turbulence.



Pressure Traces

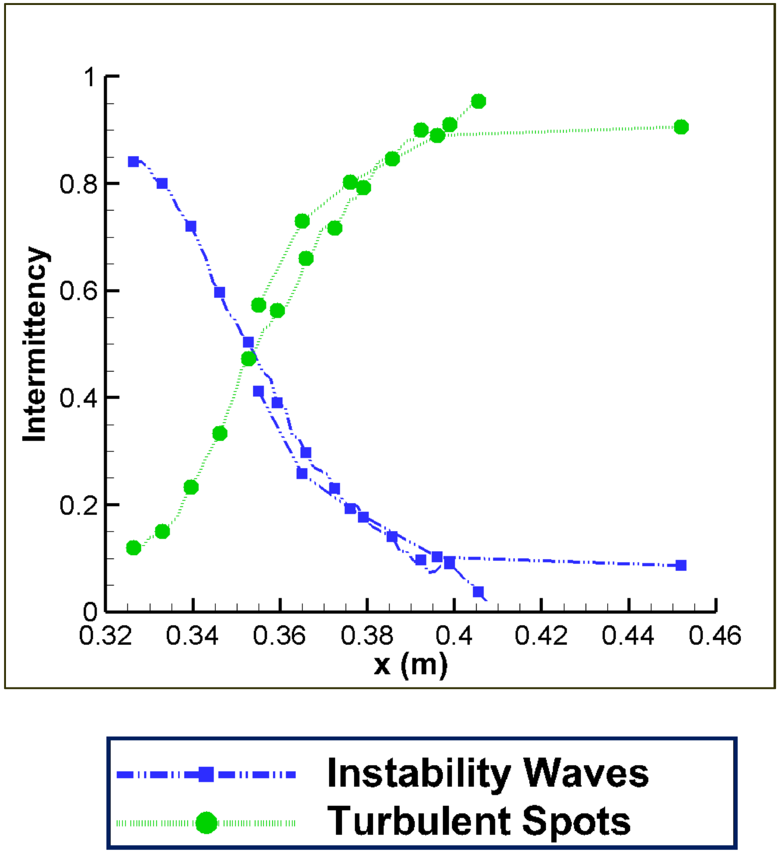
Natural Transition Statistics: Intermittency

Instability waves

- Significant part of the flow prior to development of turbulent spots.

Turbulent spots

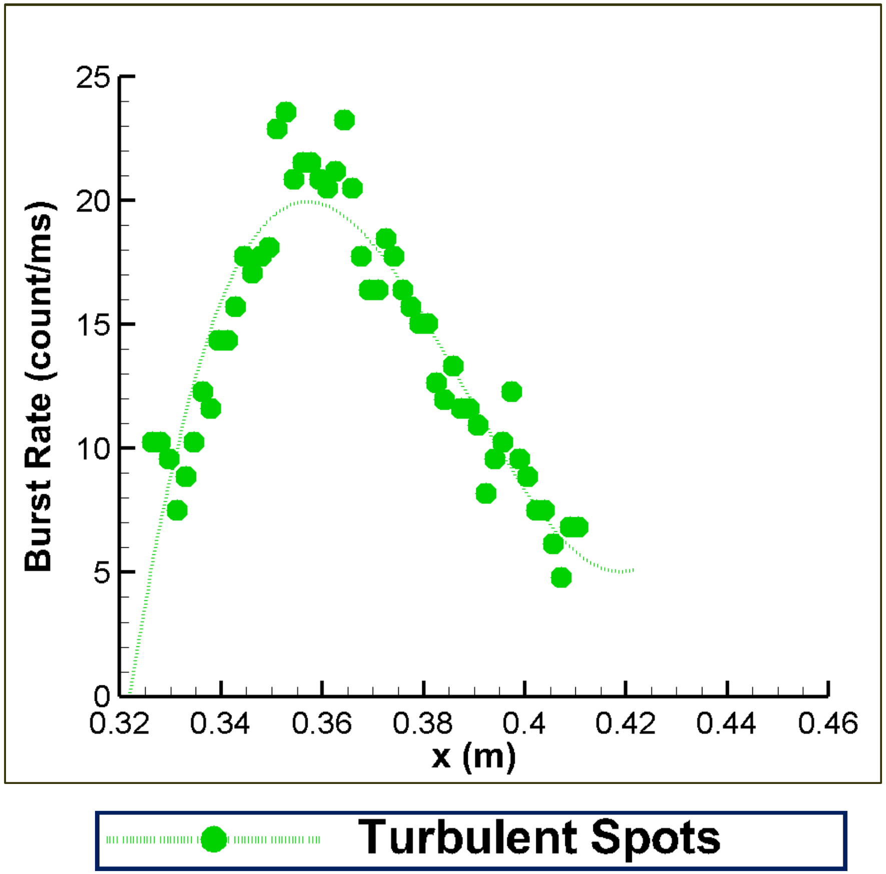
- Gradually begin to dominate flow.
- Turbulent intermittency rises as instability wave intermittency decreases.



Natural Transition Statistics: Burst Rate

Burst-rate computations shows flow switches between turbulence and waves.

- Equal burst rate for instability waves and turbulence.
- High burst rate when intermittency is near 0.5.
- Burst rate decreases as spots merge into turbulence at locations further downstream.

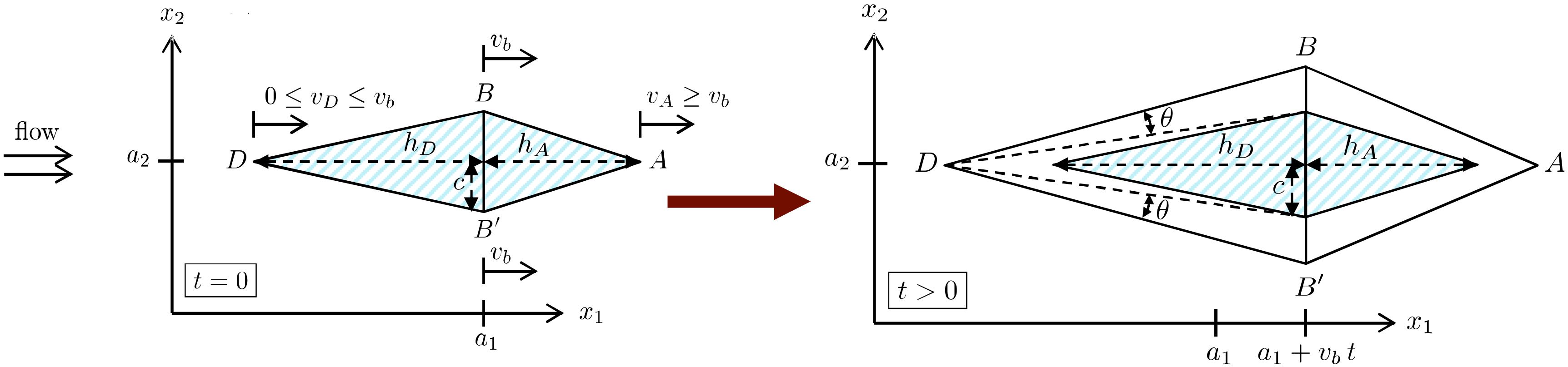


Moving Load Model of Transitional Fluctuations

Objectives:

1. Develop a probabilistic model that describes the birth, evolution, and pressure loading of multiple turbulent spots in a transitional boundary-layer
2. Collaborate with experimentalists to appropriately define important physical phenomenon that occurs during transition
3. Use experimental data to calibrate input parameters in the probabilistic model
4. Validate the probabilistic model and FE model to which it is applied by comparing response data with experiment
5. Apply to system of interest

Moving Load Model



Step 1: Generate birth times of the moving turbulent spots via jump times of Poisson point process

Step 2: Generate birthing location

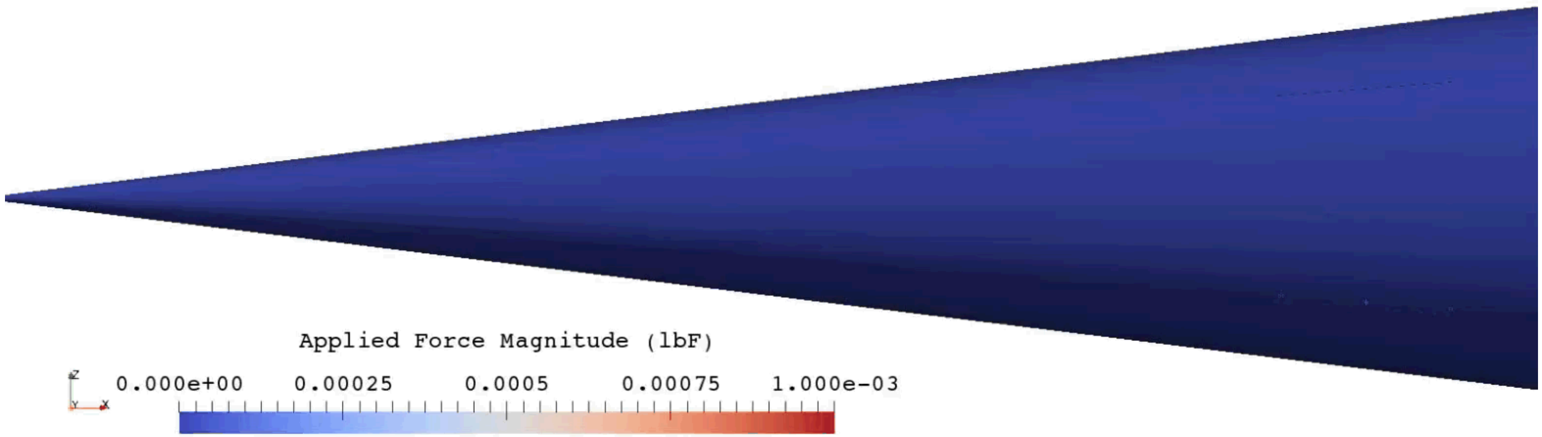
Step 3: Generate initial spot geometry

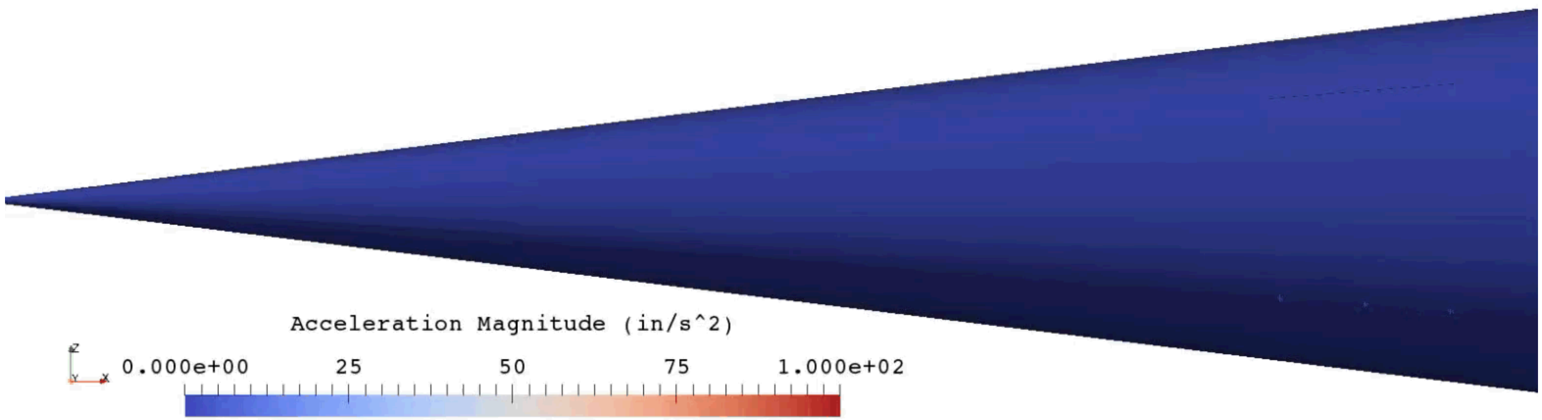
Step 4: Calculate evolution of the spot geometry in both the streamwise and spanwise directions $\forall t \in [0, T]$

Step 5: Generate the pressures of the turbulent and calmed regions of the moving spot

Step 6: Finite element mesh is loaded with the calculated moving turbulent spots and their corresponding pressures

Birth and Evolution of Turbulent Spots





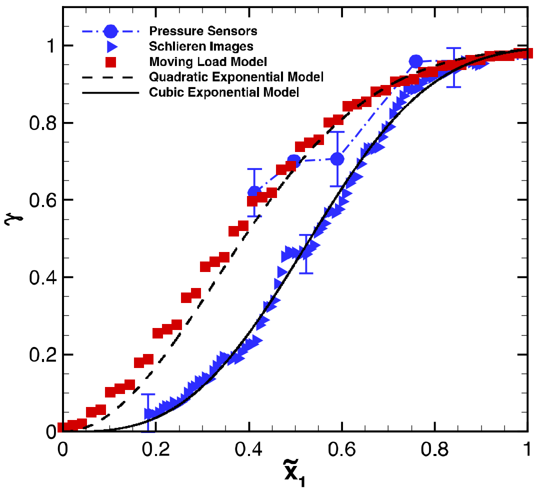
Moving Load Model Calibration

Intermittency

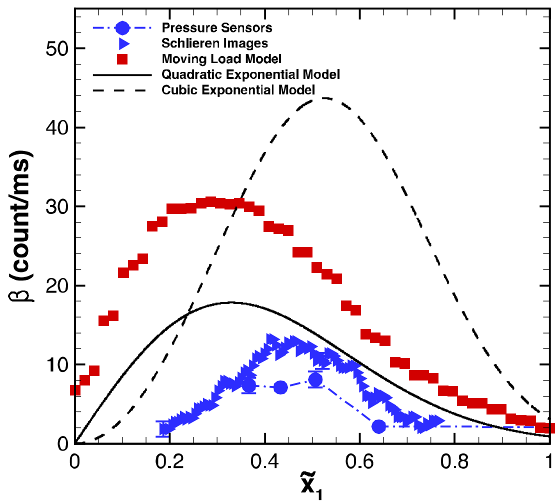
- Various values of the intensity, λ, computed for the moving load model
- The value of λ was selected such that the moving load model intermittency agreed well with pressure sensor data

Root-mean-square pressure fluctuations

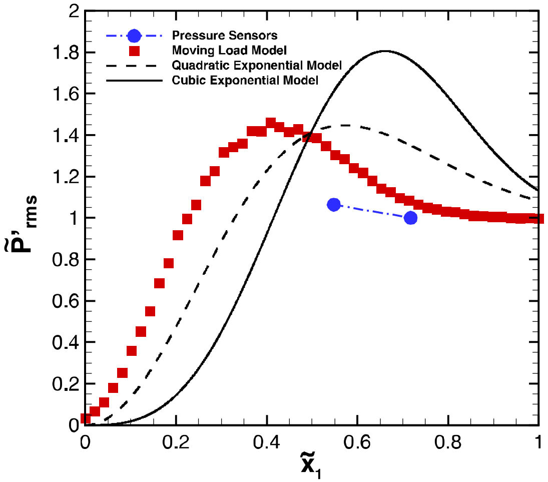
- Pressure/Force loading scaled by modulation function
- Modulation function effectively accounts for internal broadband pressure fluctuations within the turbulent portion of the spot
  - Not originally accounted for in the moving load model



Intermittency



Burst Rate



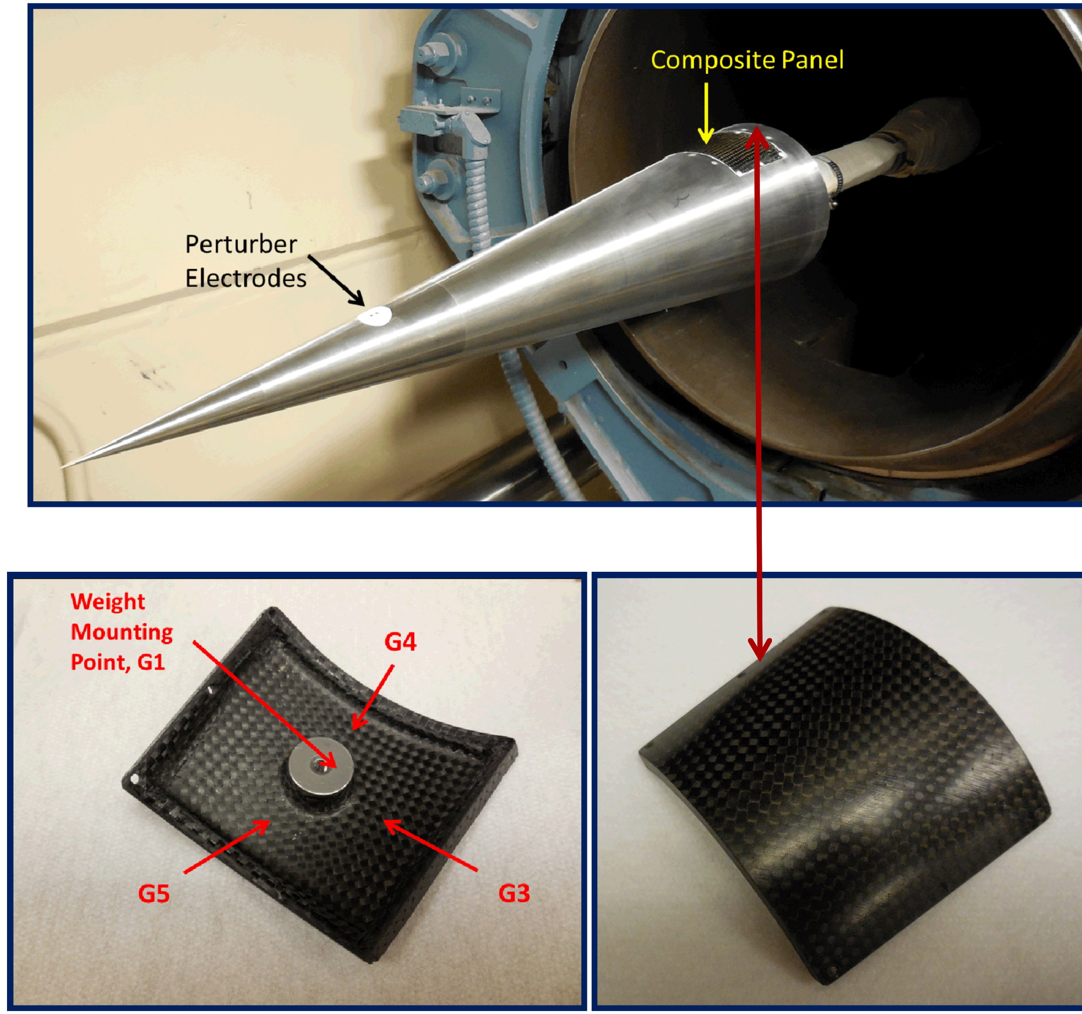
RMS Pressure

Characterizing Structural Response to this Loading

Sandia National Laboratories

Designed a cone with integrated thin panel that will vibrate from flow excitation.

- Panel response measured with accelerometers on inside of panel.
- Boundary layer was characterized using pressure sensors upstream and downstream of panel and schlieren movies.



Panel Response under Natural Transition (Noisy Flow, HWT-8)

See an elevated response to transitional boundary layers.

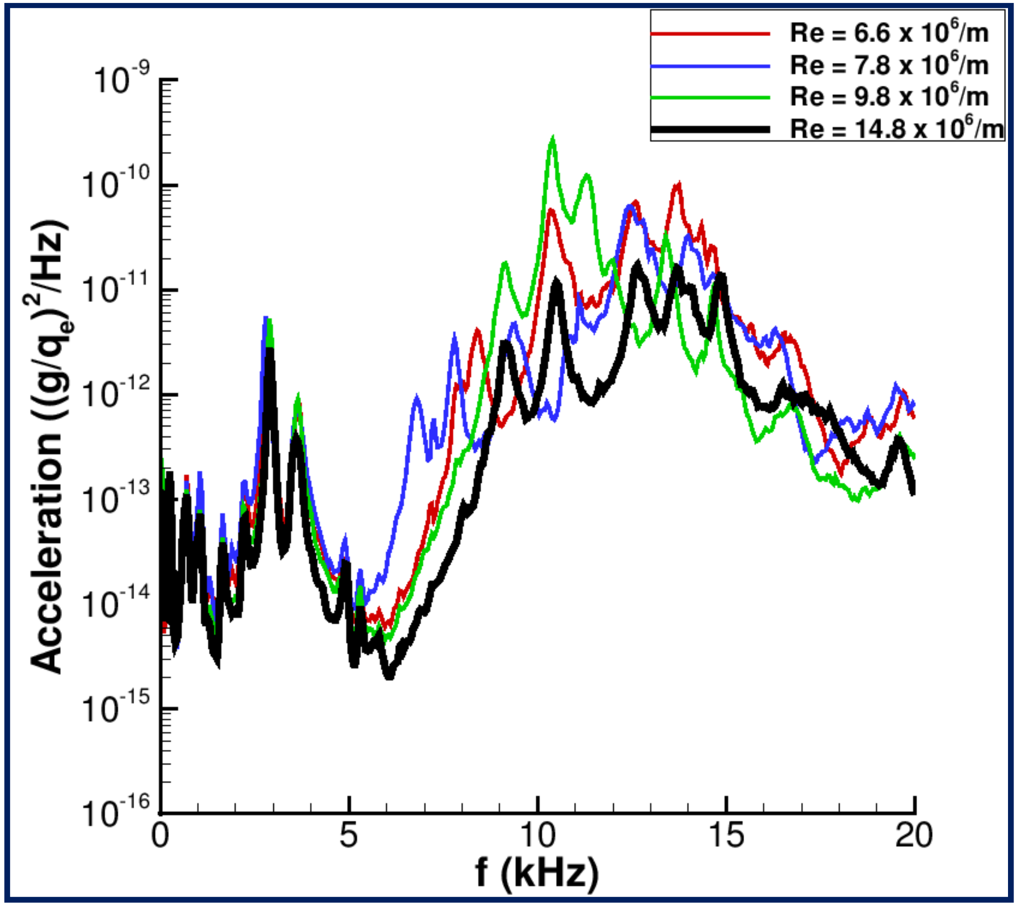
- Re = 6.6 – 9.8 x 10^6/m

Lower response to turbulent boundary layers.

- Re = 14.8 x 10^6/m

Largest differences occur at higher frequencies (5 – 20 kHz).

- This was unexpected!



Power spectra of z acceleration

Conclusions

- Semi-empirical model have been developed to describe the pressure loading under turbulent and transitional boundary layers
- Experimental pressure data were utilized to calibrate these models
  - Wind tunnel wall data at Mach 1.5 to 7.9
  - HWT cone data at Mach 5.0 and 7.9 (edge Mach 4.0 and 6.3)
- **Turbulent BL:**
  - The modeled auto spectral density agreed well with the wind tunnel data across all Mach numbers, but significantly under-predicts cone values
  - Spatial correlation data used to determine the lateral and longitudinal decay constants yielded much larger values (less correlation) than lower-speed data
- **Transitional BL:**
  - Turbulent intermittency, burst rate, and rms pressure fluctuation data inform our models.
  - Structural response calculations are just beginning, and comparisons to experimental data are expected soon.

Future Work

- DNS of HWT cone at Mach 5, 8 at high Re ~10^7/m
  - Generate pressure auto- and cross-spectra for validation of ROM's
  - Introduce tunnel disturbances to see effects of noise
  - Includes collaboration with Prof. Lian Duan, Missouri S&T
- Collaboration with Purdue to examine flared cone spectra with and without tunnel noise
- Examine additional pressure ASD curves, with Bayesian calibration of curve-fitting parameters to match wind tunnel data
- Inverse method to determine external loading from structural response measurements – first on HWT cone, then on flight data

Acknowledgments

- The authors would like to thank:
  - Rich Field, Mikhail Mesh for initial model development
  - Lian Duan of the Missouri University of Science and Technology for his predictions of the BAM6QT and HWT wind tunnel wall boundary layer properties. Ongoing work in HWT tunnel and cone DNS with freestream noise.
  - Steve Beresh of Sandia, who provided the freestream, boundary layer, and wind tunnel wall pressure data for Mach numbers of 1.5 to 3.0.
  - Jaideep Ray, Ross Wagnild, Neal Bitter, Peter Coffin for ongoing work in model validation and calibration

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- Questions?

- Backup Slides

Cross Spectral Density

- How do we utilize the wind tunnel data?

$$\Gamma(\omega, \Delta x, \Delta\theta) = \Phi(\omega)\exp\left(-i\frac{\omega\Delta\tilde{x}}{U}\right)\exp\left(-\alpha\frac{\omega\Delta\tilde{x}}{U}\right)\exp\left(-\beta\frac{\omega\bar{r}\Delta\tilde{\theta}}{U}\right)$$

- Non-dimensionally: $\Gamma(\omega, \xi, \eta) = \Phi(\omega)\mathrm{A}(\omega\xi)\mathrm{B}(\omega\eta)exp(-i\omega\xi)$
  - where $\mathrm{A}(\omega\xi) = \exp(-\alpha\omega\xi)$ and $\mathrm{B}(\omega\eta) = \exp(-\beta\omega\eta)$ are the coherence functions

- The experimental data of multiple sensors are processed to provide us with spatial correlations, $\mathrm{R}(\xi)$ and $\mathrm{R}(\eta)$ such that: $\mathrm{R}(\xi) \propto \int_0^\infty \Phi(\omega)A(\omega\xi)\cos(\omega\xi)\mathrm{d}\omega$ and $\mathrm{R}(\eta) \propto \int_0^\infty \Phi(\omega)B(\omega\eta)\mathrm{d}\omega$

- We approximate $\Phi(\omega)$ with a simple exponential function, allowing us to analytically determine appropriate values for $\mathrm{A}(\omega\xi)$ and $\mathrm{B}(\omega\eta)$

Theory (Improved ASD Model)

- Boundary layer edge and wall properties are obtained from a variety of sources:
  - TWT Wall: Directly measured
  - BAM6QT and HWT Wall: Estimated by Duan using combination of correlation and RANS CFD*
  - HWT Cone: Simulated
    - Mean flow simulated using DPLR CFD code
    - BL edge detected when $\frac{h_{0,j} - h_w}{h_{0,\infty} - h_w} = 0.999$
    - **BL thickness verified by comparing to Schlieren:**
      - **Mach 5: RANS 2.5 mm, Schlieren 2-2.7 mm**
      - **Mach 8: RANS 2.9 mm, Schlieren 2.6-3.1 mm**
    - **BL edge conditions verified by comparing to Taylor-Maccoll solutions**

τ_{wall} = wall shear stress
δ = boundary layer thickness
U_e = edge velocity
M_e = edge Mach number
q_e = edge dynamic pressure
δ^* = displacement thickness

*L. Duan and M. Choudhari, "Analysis of Numerical Simulation Database for Pressure Fluctuations Induced by High-Speed Turbulent Boundary Layers," Presented at the 44th AIAA Fluid Dynamics Conference, Atlanta, GA, June 2014.

Outline

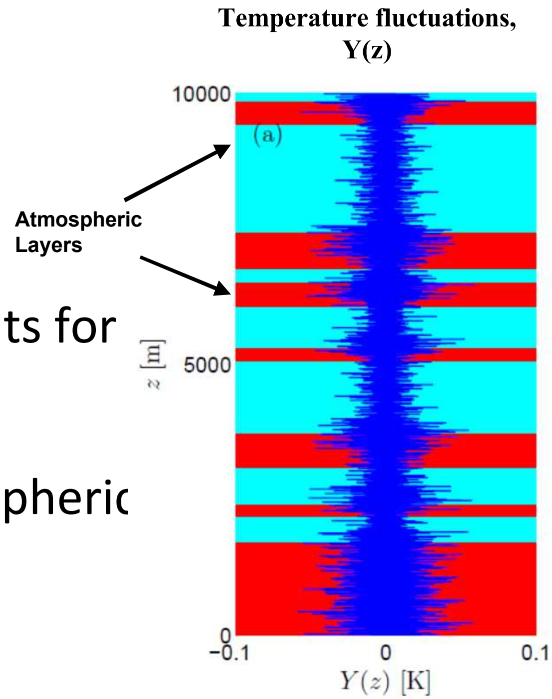
- Aerosciences at Sandia National Labs
- Intro Reentry Random Vibration
  - Turbulent Boundary Layer
  - Random Atmosphere
  - Transition
- Conclusions
- Future Work

Atmospheric Loading

- Motivated by realization that the length scale to drive low frequencies ~ 1 kHz is longer than any RB:

$$\text{length scale} = \frac{\text{velocity}}{\text{frequency}} \sim \frac{10\ \text{kft/s}}{1\ \text{kHz}} = 10\ \text{ft}$$

- Originally looked at particle impacts but this accounts for portion of overall response

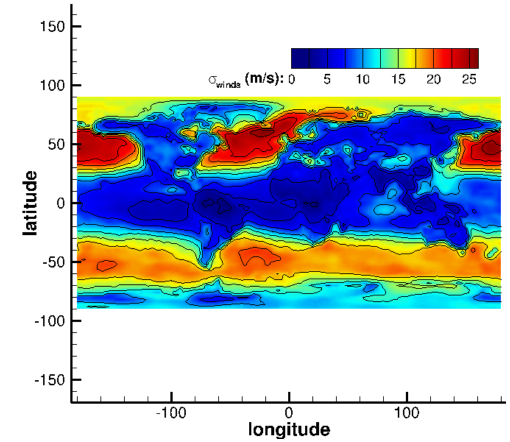


- Developed 1D model to scope loading due to atmospheric
  - Fluctuations in pressure, density, and temperature are layers of relatively calm or turbulent atmosphere
  - The resulting fluctuating drag on an RV flown through this varying atmosphere loads the vehicle axially, but no mechanism is in place for lateral variations
  - This has demonstrated the significance of atmospheric loading, but improvements to the mode were necessary

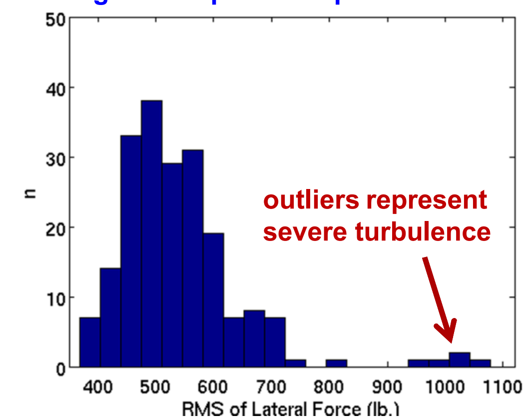
Atmospheric Loading

- Improvements were necessary to capture lateral accelerations for a vehicle traveling at nominally zero angle of attack.
- An improved capability was developed using NASA's Earth Global Reference Atmospheric Model (GRAM) software:
  - Simulates spatial and temporal perturbations in the thermodynamic variables and winds
  - Complete seasonal and monthly variability
  - Turbulence severity controlled by statistical parameters and varied based on a random seed
  - Software has been extensively tested and utilized in the Space Shuttle program for same flight regimes as RV's fly!

Near-surface wind standard deviation

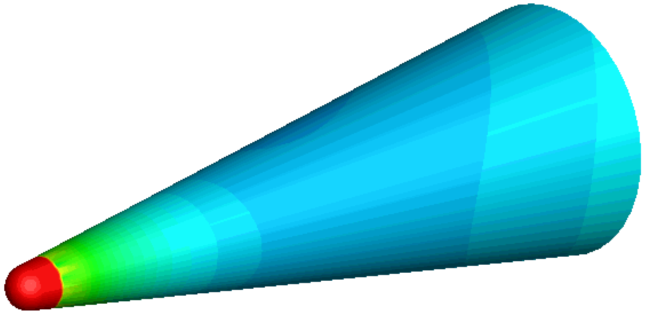


Loading in multiple atmosphere realizations



Atmospheric Loading

- To correctly drive the structural response due to atmospheric loads, accurate pressures are required over the vehicle surface at small time steps ~10^{-4} s
  - Requires a fast and accurate method
  - CFD is accurate but an entire trajectory would take too long to complete!
  - Instead, we use a correlation and theory-based code, *AEROP*, founded on the work of Wells and Thornley[1]
    - Works on spherically-capped cones at supersonic and hypersonic conditions
    - **It's Fast!** 30-second trajectory at 10 kHz in about an hour
    - Validated against higher-fidelity codes at Sandia



[2]P. Wells and P. Thornley, "Blunt Cone Pressure Correlations for Supersonic and Hypersonic Flow," AIAA Paper 96-2447, Presented at the 14th AIAA Applied Aerodynamics Conference, New Orleans, LA, June 1996.