Using Frontera for the Direct Numerical Simulation of Hypersonic Flows

Daniel J. Bodony, Bryson Sullivan, and Fabian Dettenrieder
Aerospace Engineering

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Dr. Sarah Popkin
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A Definition of Hypersonics

X-51 Waverider (Mach 5)

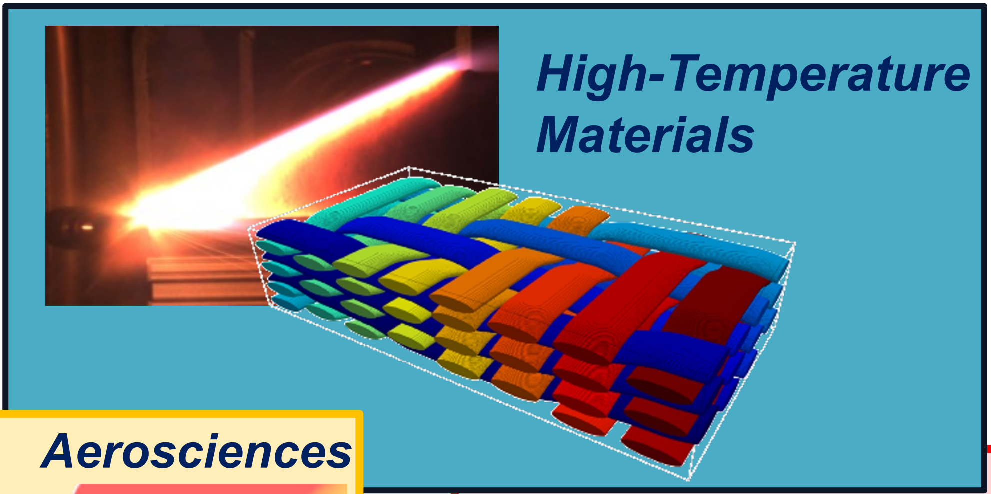
HTV-2 (Mach 20+)

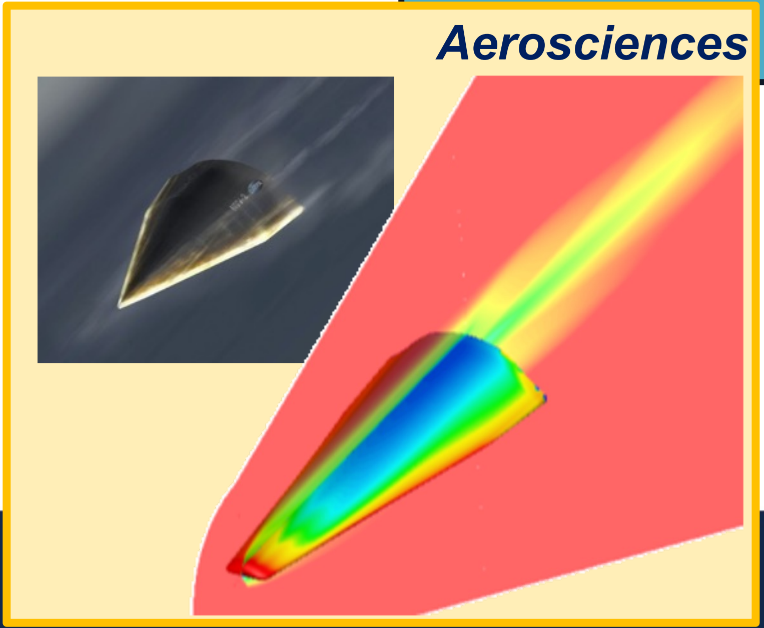
Stardust (Mach 43)

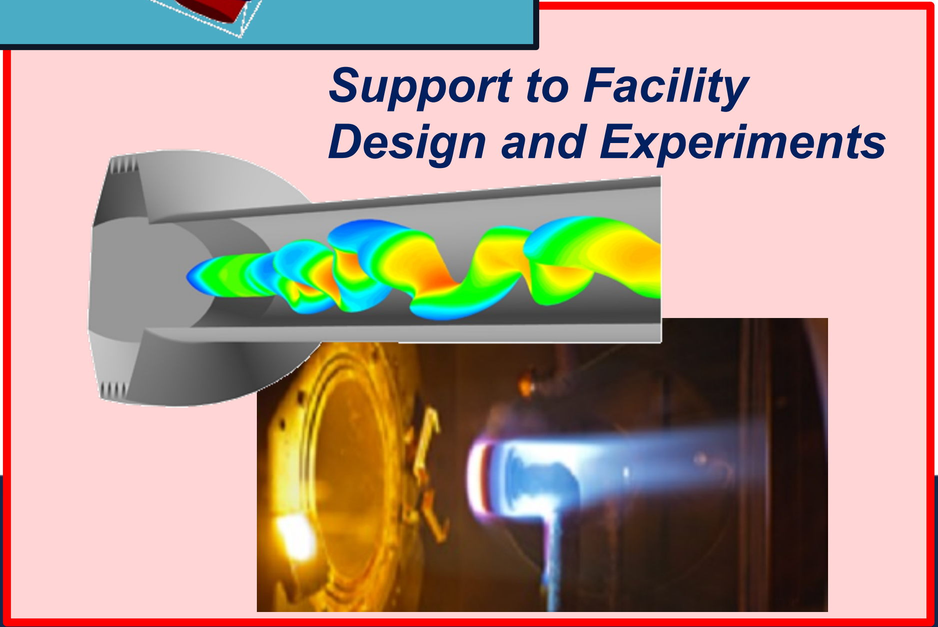
SCRAMJET — Tactical Boost Glide — Reentry Capsule

$$\text{Mach \#:} \quad M = \frac{\text{velocity}}{\text{speed of sound}}$$

Modeling Challenges





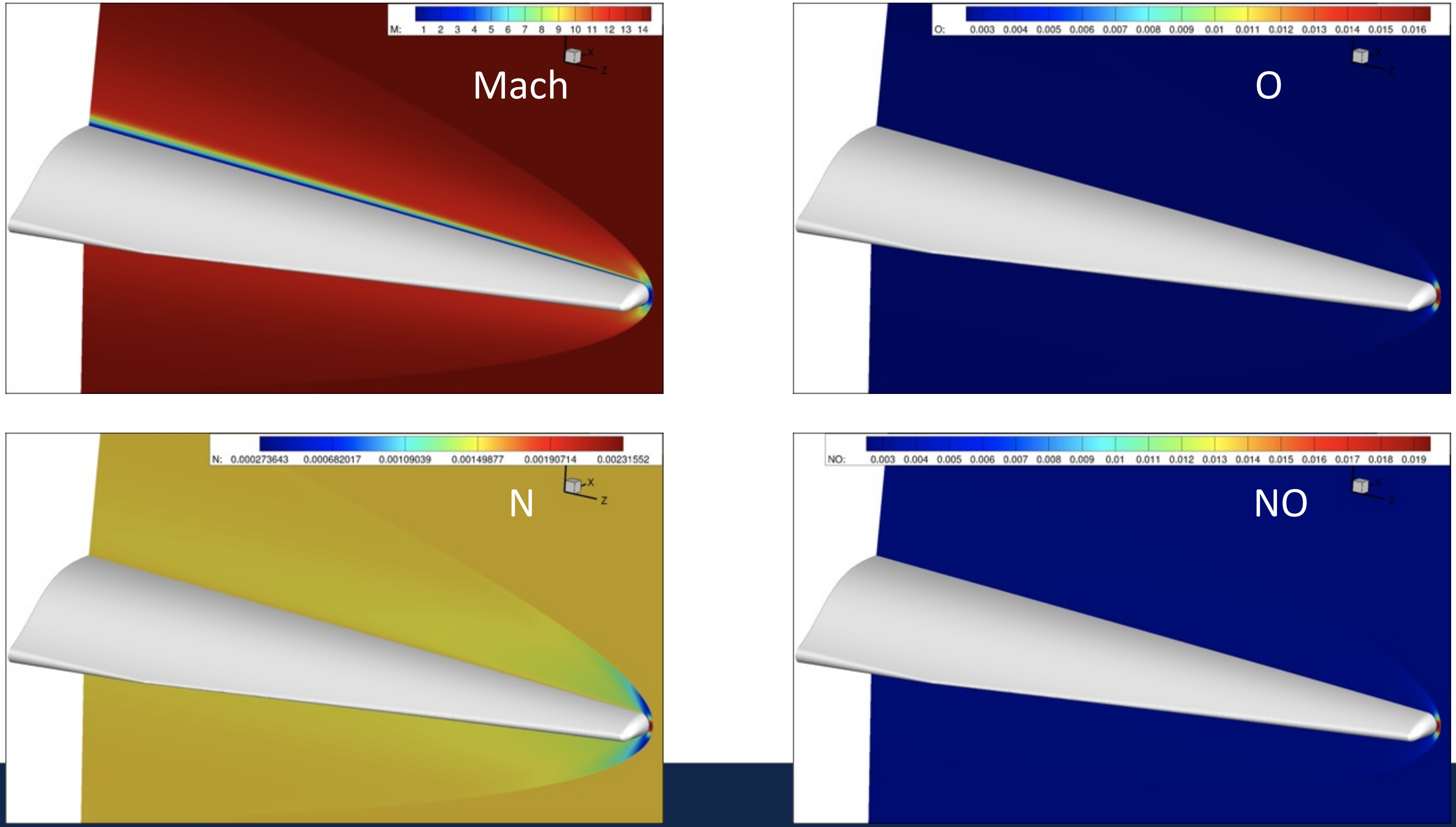


Hypersonics: An HPC Grand Challenge

- Multiscale in space: 10^{-9} to 10^{1} m
- Multiscale in time: 10^{-10} to 10^{2} s
- Domain-specific codes (MD, DSMC, FEM, CFD, rad, E&M)
- Different codes map differently onto heterogeneous hardware
- Inter-code orchestration
- UQ & MDO need multiple realizations
- (Didn't even discuss I/O…)

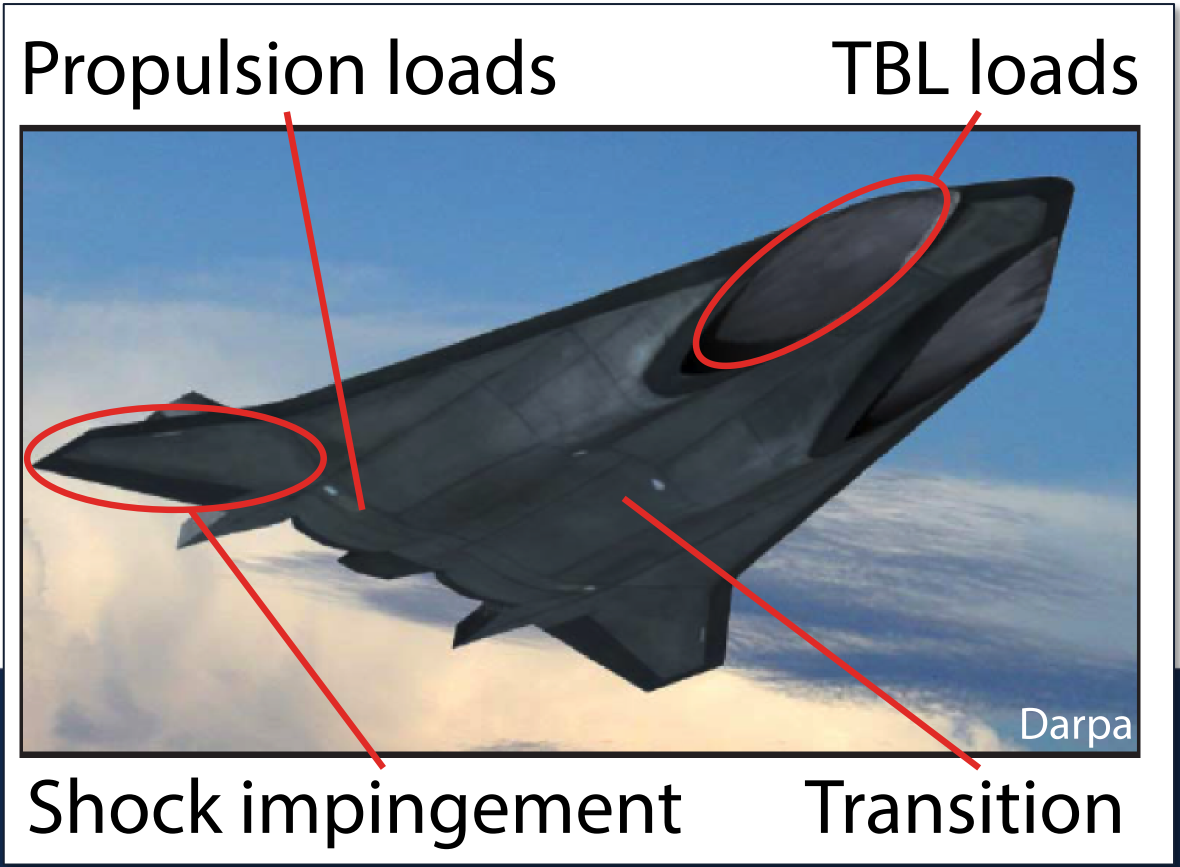
Example Mach 15 Flow Field

5-species air, 100 kft, 800 Frontera nodes

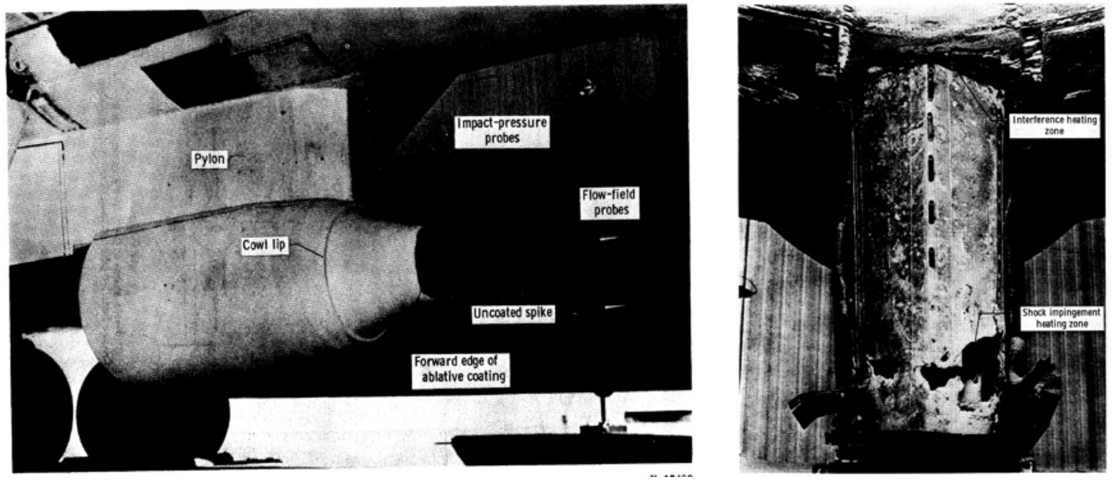


Aerosciences: Key Understanding Gap

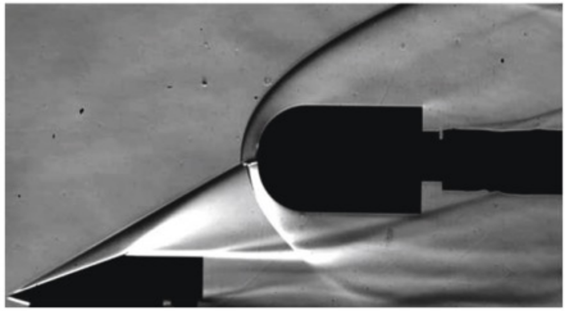
- Extracted from Boeing and Lockheed pre-PDR designs of Mach 5-7 reusable vehicle (AFRL-RB-WP-TR-2010-3068, -3069, and summarized by Eason et al., AIAA Paper 2013-1747).
- “Can only approximate the acoustic environment …”
- “Identification of critical thermal, mechanical, and acoustic loads …”
- “Predicting aero-elastic characteristics of thin metallic structure at high T …”



Case Study 1



Unanticipated shock-shock interaction caused loss of “engine”, severe damage to pilon (Watts, 1968)



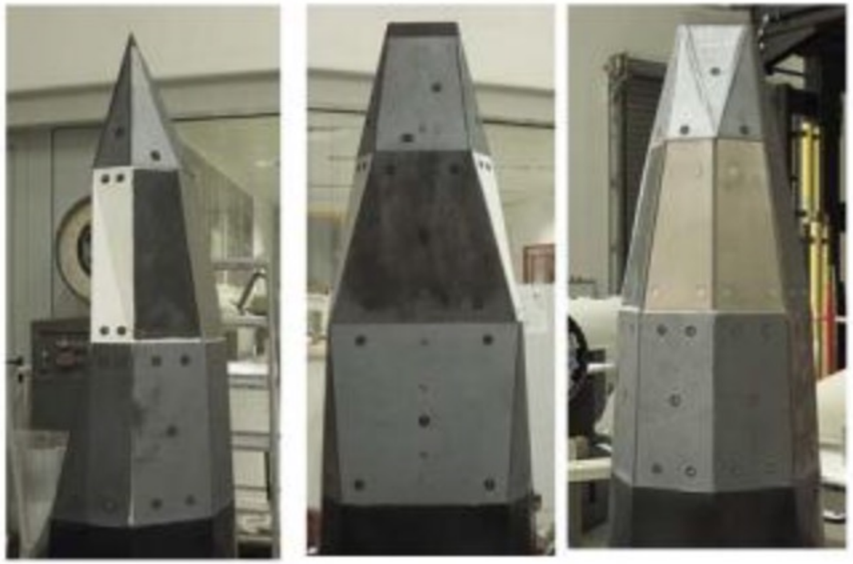
X-15-2 carrying pilon-mounted dummy scramjet
Credit: USAF

Edney Type IV shock-shock interaction leads to localized intense impinging jet (Chettles et al., 2005)

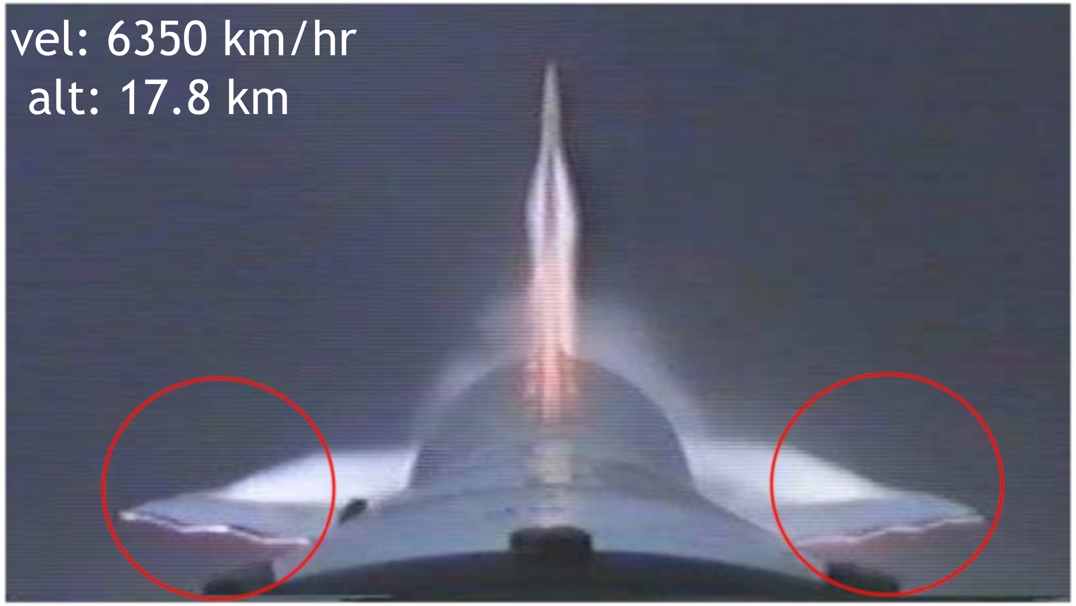
Case Study 2

- SHEFEX-I (Sharp Edge Flight Experiment) by DLR in 2005
- Purpose: test flat-sided design and TPS concepts for re-entry vehicles

Launch from Andoya, Norway



Vehicle nose carried primary experiment of flat paneled hypersonic structure



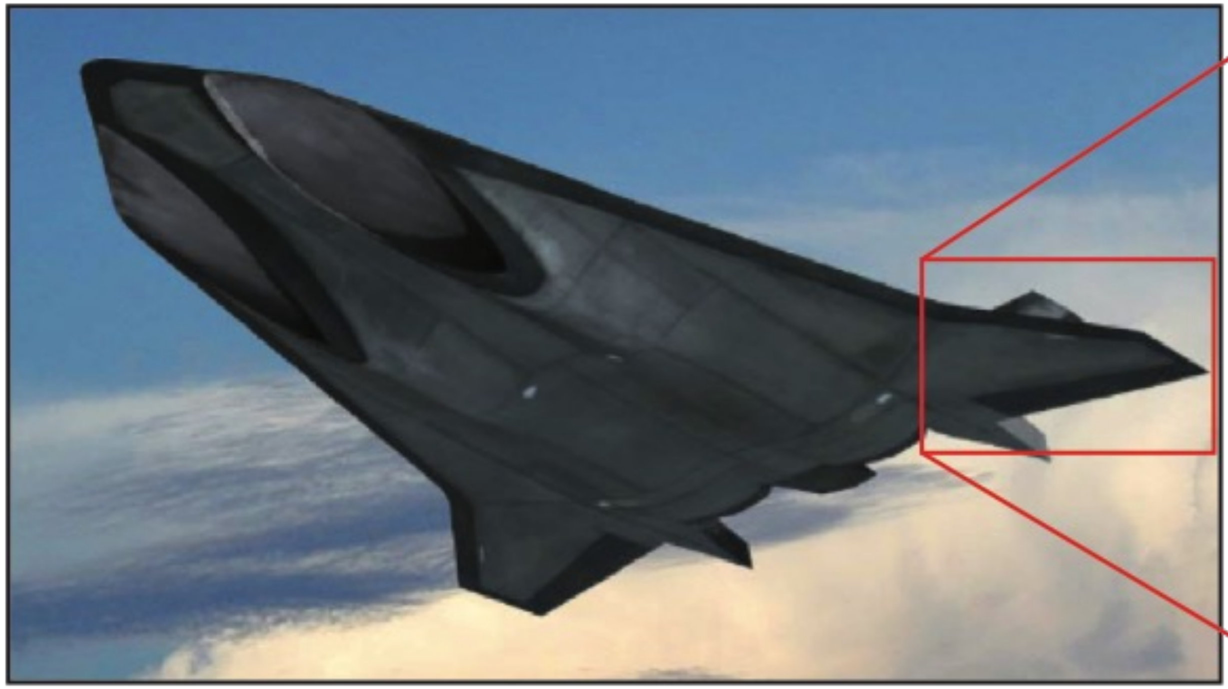
Rear section of SHEFEX-I during decent. Circles indicate control surface LE deformation due to FTSI.

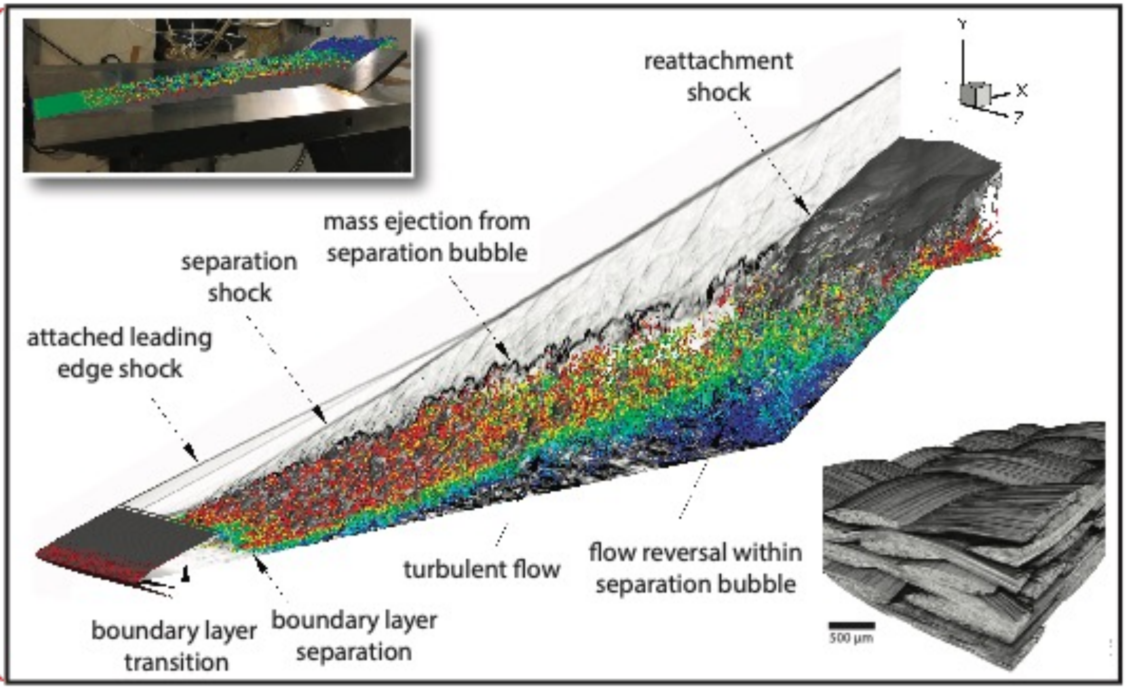
All figures credit: Longo et al., 2006

Frontera: Study FSI of a 35 deg ramp

TBL Loads

Propulsion Loads



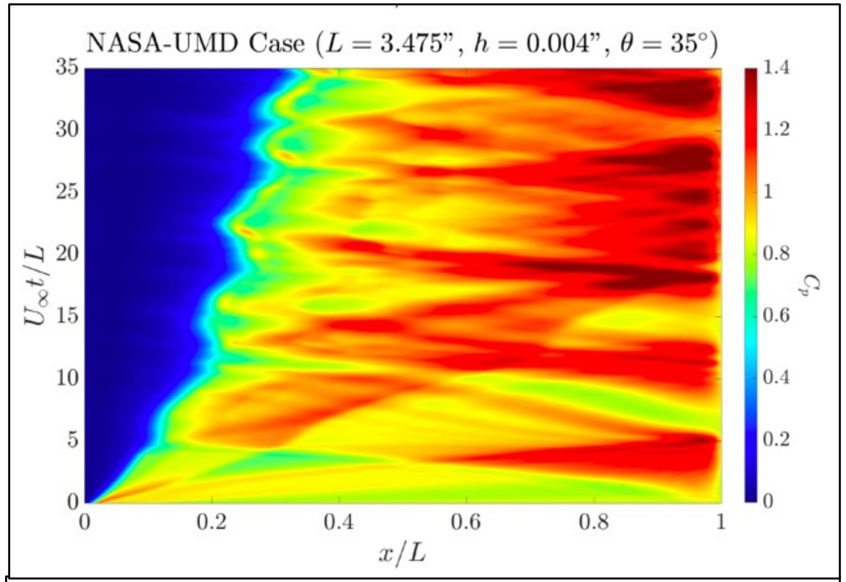


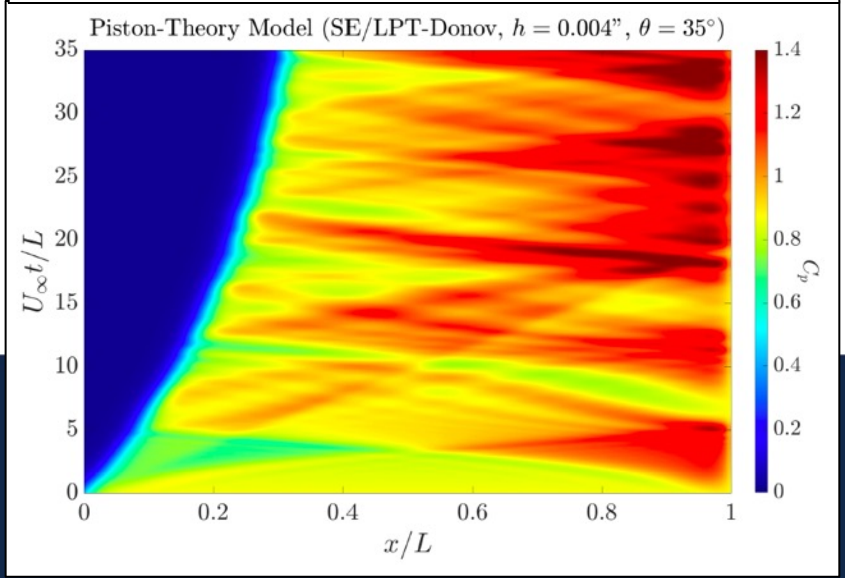
Transition

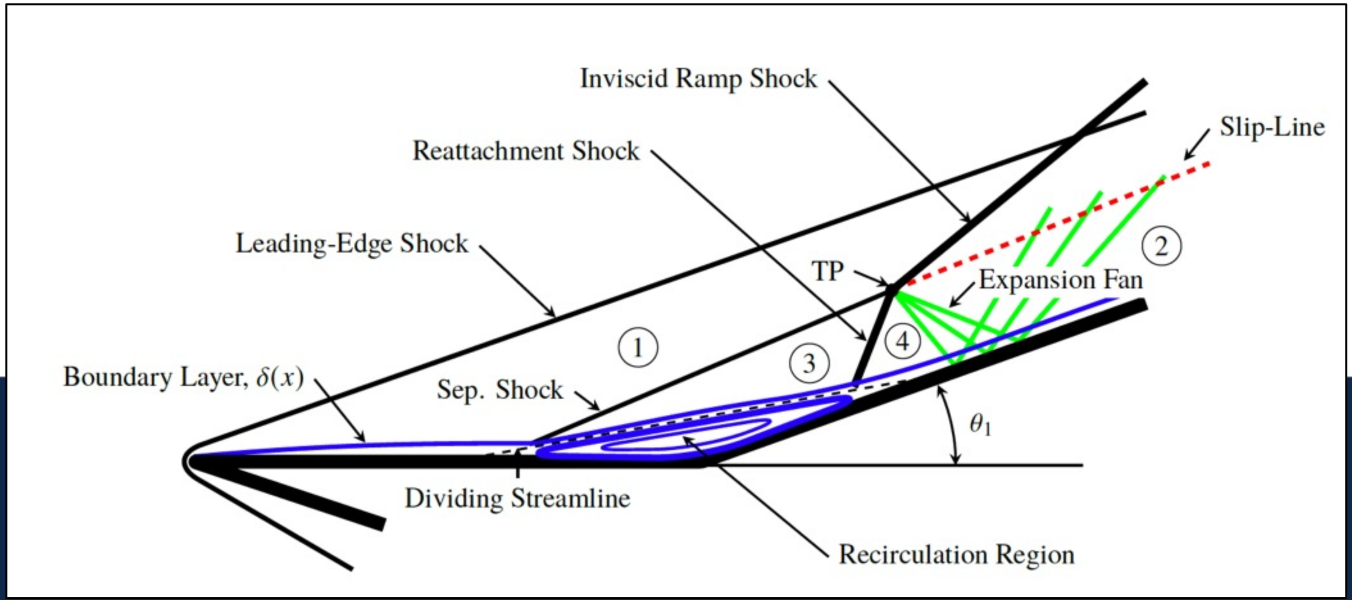
Shock Impingement

Goal: Useful Reduced-Order Model

- Fluid prediction dominates cost of FTSI DNS
- Also represents the biggest unknown in OEM design and analysis
- Developed a multiple-shock version of local Piston theory (Sullivan et al., AIAAJ, 2020)

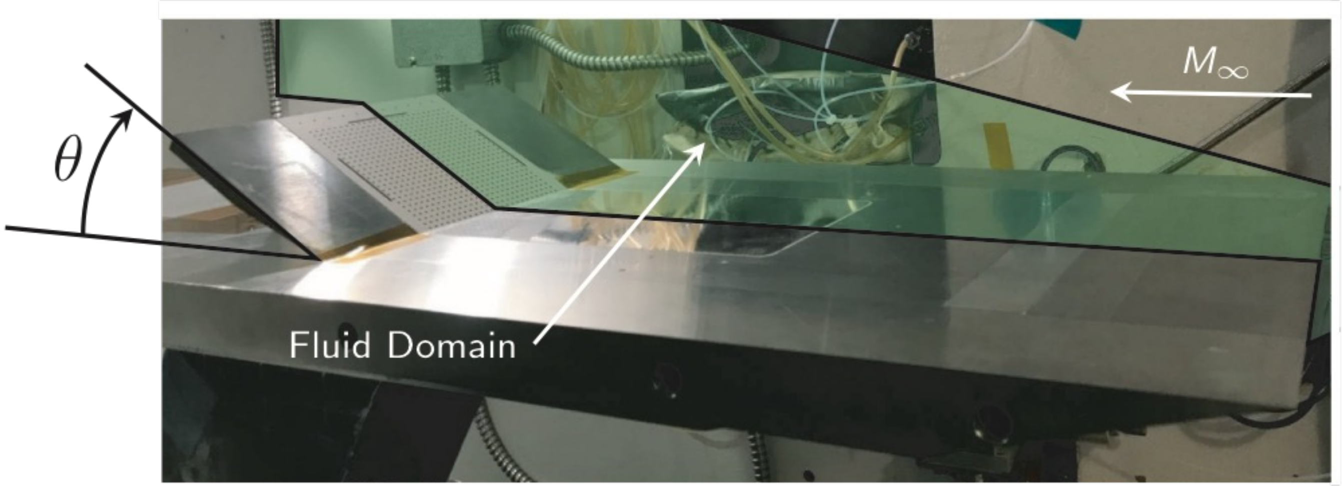






High-Speed FTSI: Shock on Control Surface

- Flow conditions:
  - Mach 6
  - T_0 = 522 K
  - P_0 = 3.2 MPa
  - unit Re = 23.6 x 10^6 / m
- Model conditions
  - 4140 stainless steel plate
  - milled compliant section
  - 0.032” tested



Credit: Tom Whalen and Stuart Laurence (UMD)

- Test time ~ 5 sec
  - Tunnel started with model retracted
  - Model raised in ~ 3 sec
  - Data collected for ~ 5 sec

Sullivan et al., AIAA J, 2020

Anecdote: Wanted to test 0.016” but NASA safety wouldn’t allow it for fear of tunnel unstart.

Computational Approach

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0$$

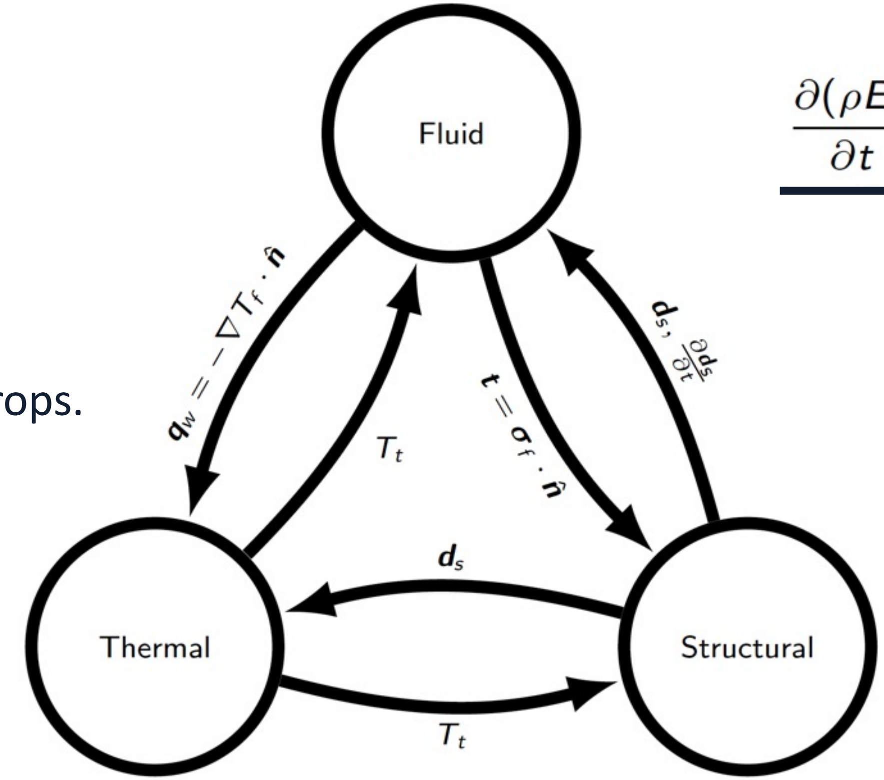
$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j + p\delta_{ij} - \tau_{ij}) = 0$$

$$\frac{\partial (\rho E)}{\partial t} + \frac{\partial}{\partial x_j}[u_j(\rho E + p) + q_j - u_i \tau_{ij}] = 0$$

Finite difference SBP-SAT + WENO
Generalized, deformable coords.

Coupling:
- C++ MPI layer
- Multirate time advancement

Material model:
- Isotropic
- Compressible Neo-Hookean
- Temp. dependent material props.



$$\rho C \dot{\Theta} + \nabla \cdot \boldsymbol{q} = 0$$

Quadratic FE
Crank-Nicolson

$$\nabla \cdot \boldsymbol{\sigma} + \rho_s \boldsymbol{b} = \rho_s \ddot{\boldsymbol{d}}$$

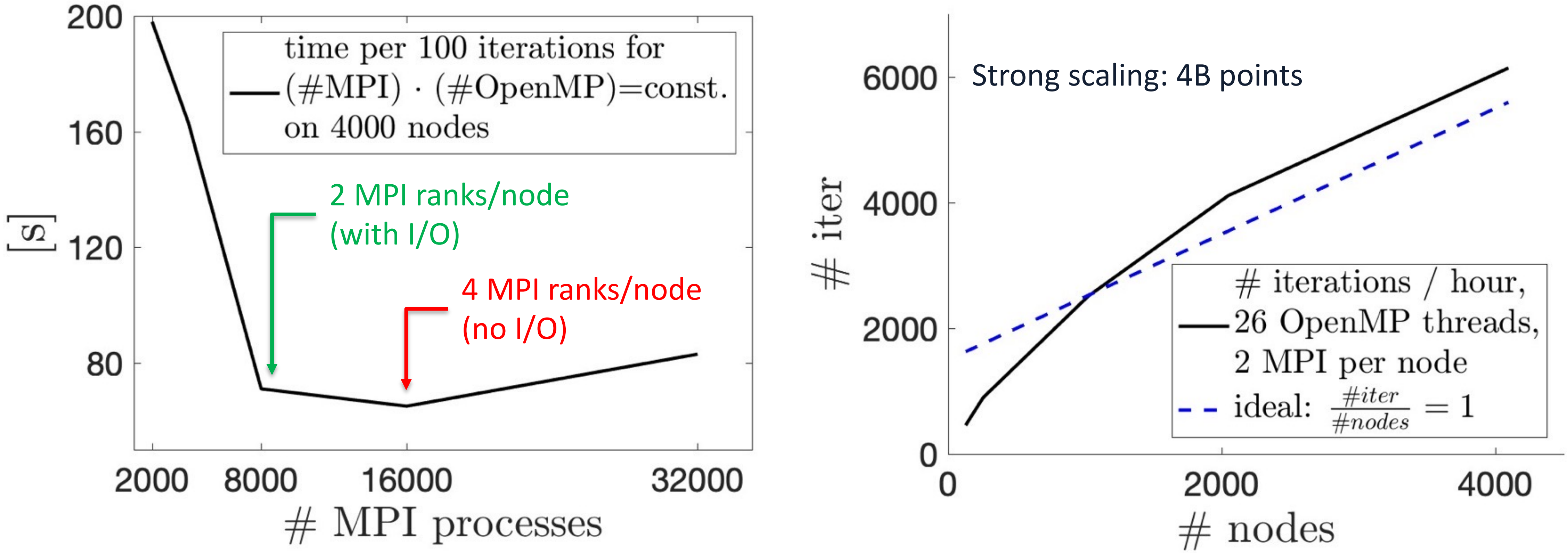
Quadratic FE
Multiplicative Split
Newmark-Beta

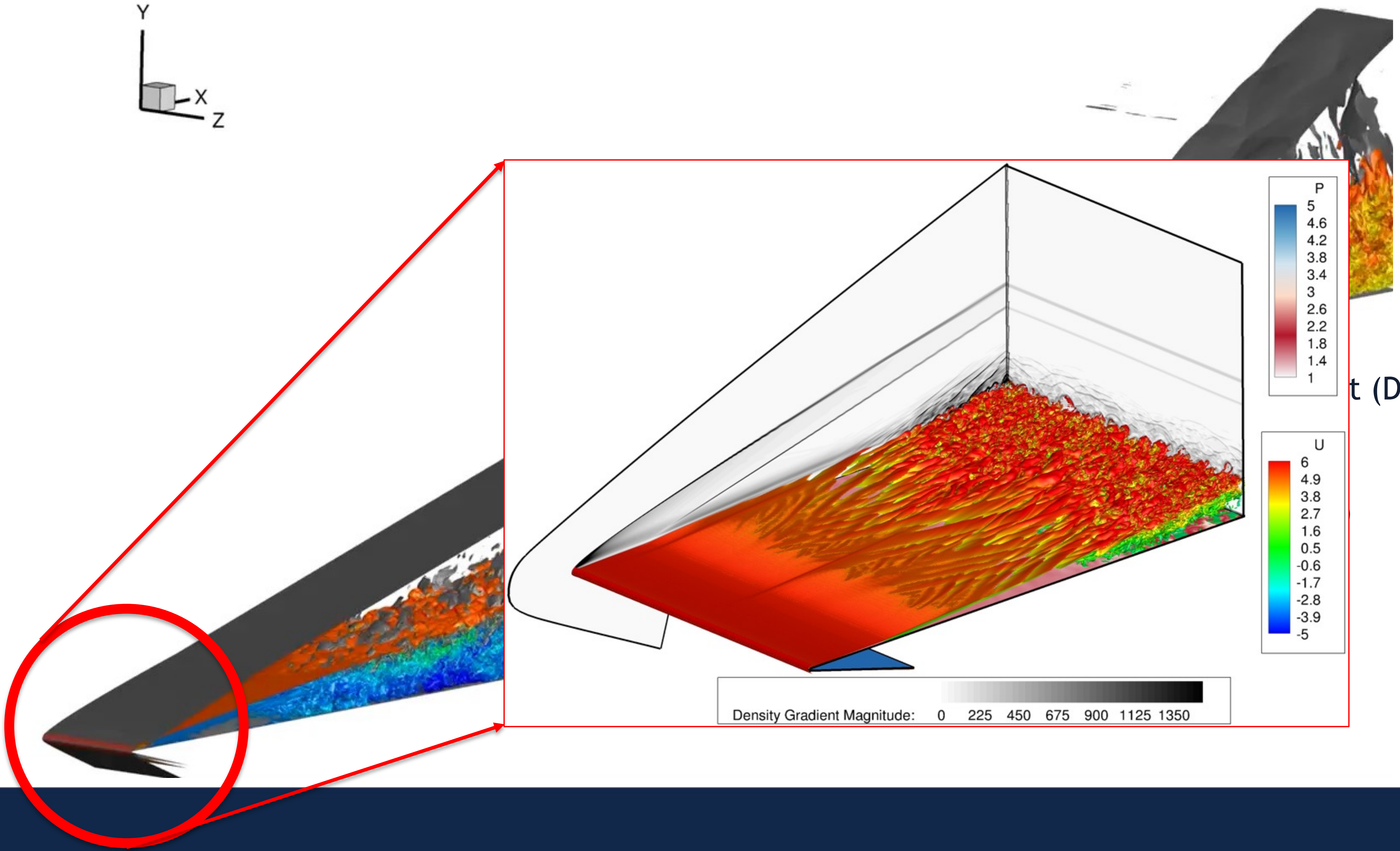
Sullivan et al., AIAA J, 2020

Computational Infrastructure

- Additional Capabilities
  - Multi-rate time integration
  - Structured overset
    - Geometric flexibility
    - Deformable / moving
  - Different grids = different physics models
  - Cantera-informed chemistry (Prometheus)
  - Multiphysics linear operator (global modes, input/output, resolvent analysis)
- Code details
  - C++ infrastructure
  - Physics kernels – extensible
  - MPI + OpenMP (≥ 4.5)
  - GPU offloading via OpenMP
- Thermo-mechanical
  - Built on MFEM
  - Includes TPS models, radiation, …

Performance on Frontera





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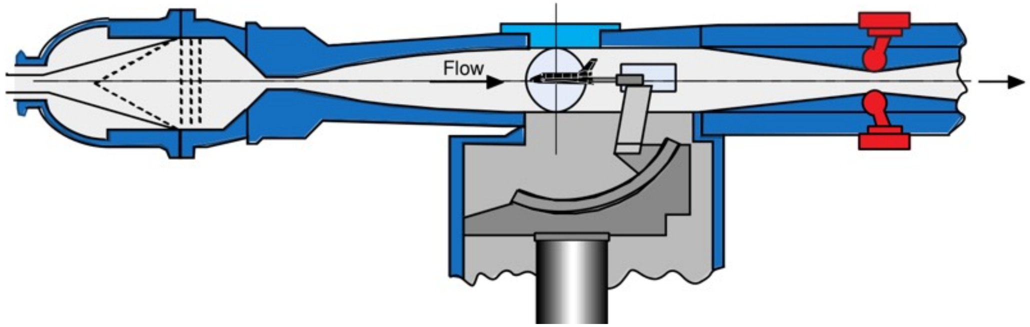
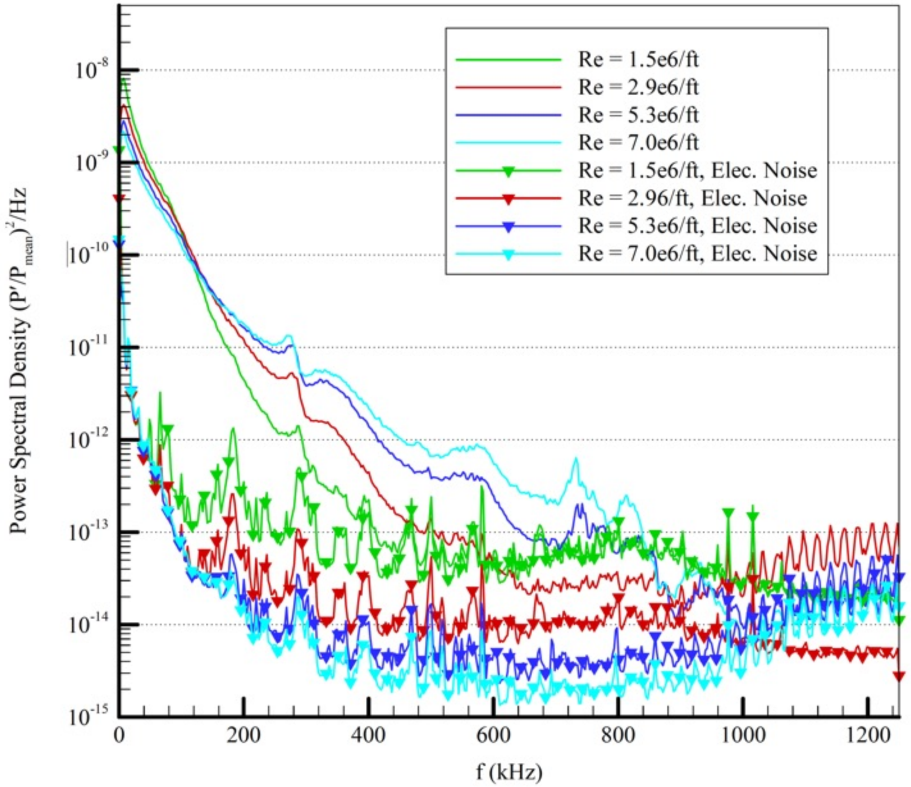
-0.6
-1.7
-2.8
-3.9
-5
Density Gradient Magnitude: 0 225 450 675 900 1125 1350

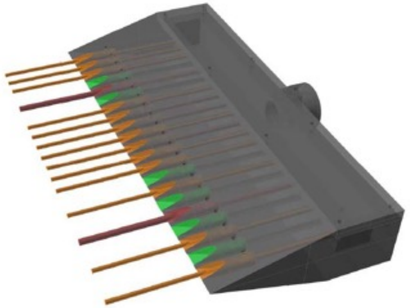
t (DNS)

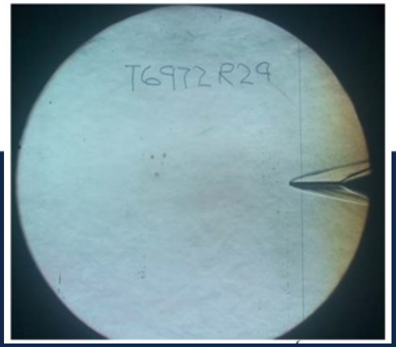
Return to NASA LaRC M6 Tunnel Details

- Tunnel walls are flat and radiate sound
- Sound impacts model:
  - Modifies flat plate boundary layer transition
  - Changes FTSI
  - No diagnostics to suggest where BL transitions
- Resort to including acoustic field in the 3D calculations
- Rufer & Berridge (AIAA 2012-3262)









Model NASA LaRC M6 Tunnel Noise

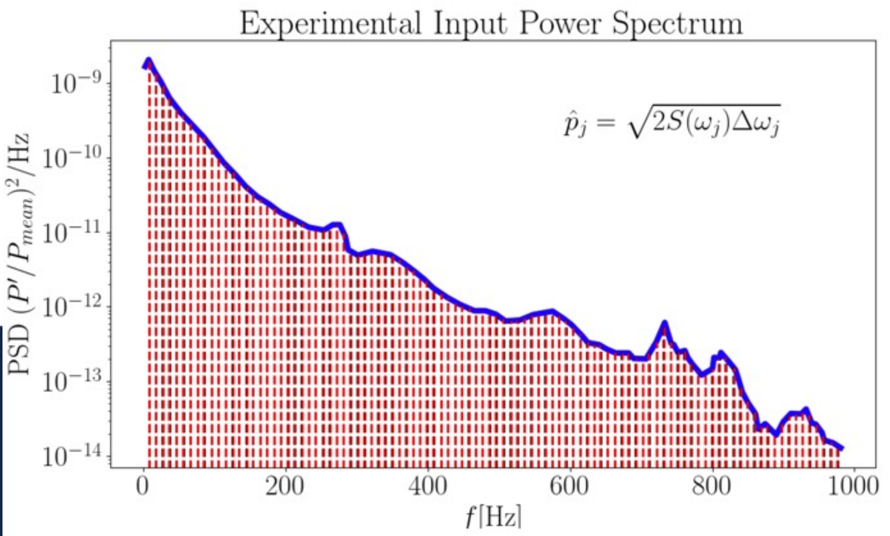
- Take measured PSD from Kulite / PCB rake
- Apply Tam *et al.* PSD discretization
- Apply inverse pitot-tube transfer function (Chaudhry & Candler)
- Assume plane wave field:

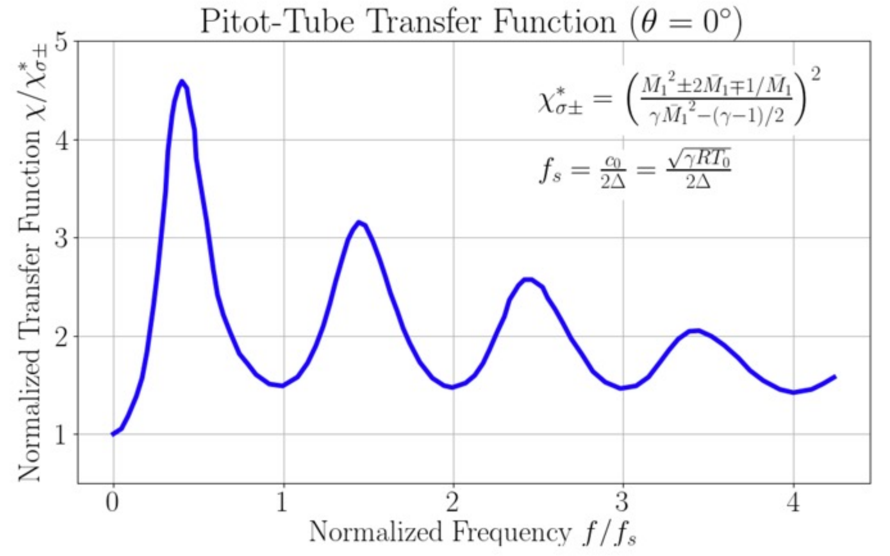
$$p'(\boldsymbol{x},t) = p_\infty \sum_{j=1}^{N_w} \hat{p}_j e^{i(\boldsymbol{k}_j\cdot\boldsymbol{x} - \omega_j t + \tilde{\phi}_j)}$$

$$= p_\infty \sum_{j=1}^{N_w} \left(\sqrt{2\hat{S}(\omega_j)\Delta\omega_j}\right) e^{i(\boldsymbol{k}_j\cdot\boldsymbol{x} - \omega_j t + \tilde{\phi}_j)}$$

$$\rho'(\boldsymbol{x},t) = \frac{1}{c_\infty^2} p'(\boldsymbol{x},t) = \frac{1}{\gamma} \sum_{j=1}^{N_w} \hat{p}_j e^{i(\boldsymbol{k}_j\cdot\boldsymbol{x} - \omega_j t + \tilde{\phi}_j)}$$

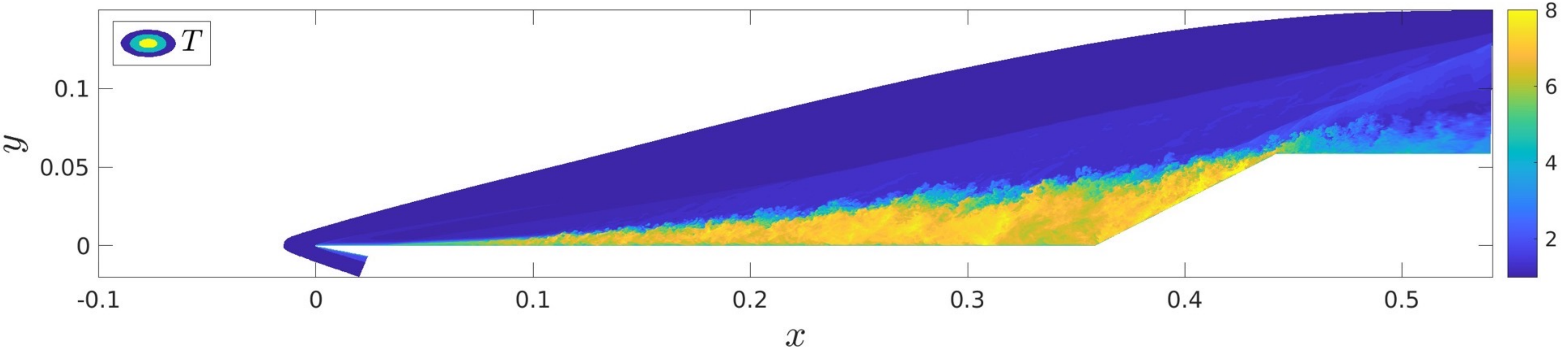
$$\boldsymbol{u}'(\boldsymbol{x},t) = \frac{c_\infty}{\gamma} \sum_{j=1}^{N_w} \hat{p}_j \frac{\boldsymbol{k_j}}{\|\boldsymbol{k_j}\|} e^{i(\boldsymbol{k}_j\cdot\boldsymbol{x} - \omega_j t + \tilde{\phi}_j)}$$





3D DNS with NASA LaRC M6 Tunnel Noise

- 6 Billion grid points
- Running on NSF Frontera with 1024 nodes (57K cores)



Summary

- There are many FTSI scenarios that are critical for hypersonic flight
- Historical use of noisy ground tunnels may impact our FTSI models at flight conditions
- Fundamental investigations coupled with good modeling (cf. McNamara) and recent experiments (cf. AEDC) are going to impact our understanding of FTSI at high Mach numbers
- Much work is needed on “basic” flows

Contact Information

Daniel J. Bodony
Blue Waters Professor
Department of Aerospace Engineering
Department of Mechanical Science and Engineering (by courtesy)
306C Talbot Labs
104 S. Wright St.
Urbana, IL 61801
T: (217) 244-3844
bodony@illinois.edu
http://acoustics.ae.illinois.edu

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