NASA LaRC Contribution to the AePW High Speed Working Group Test Case, RC-19

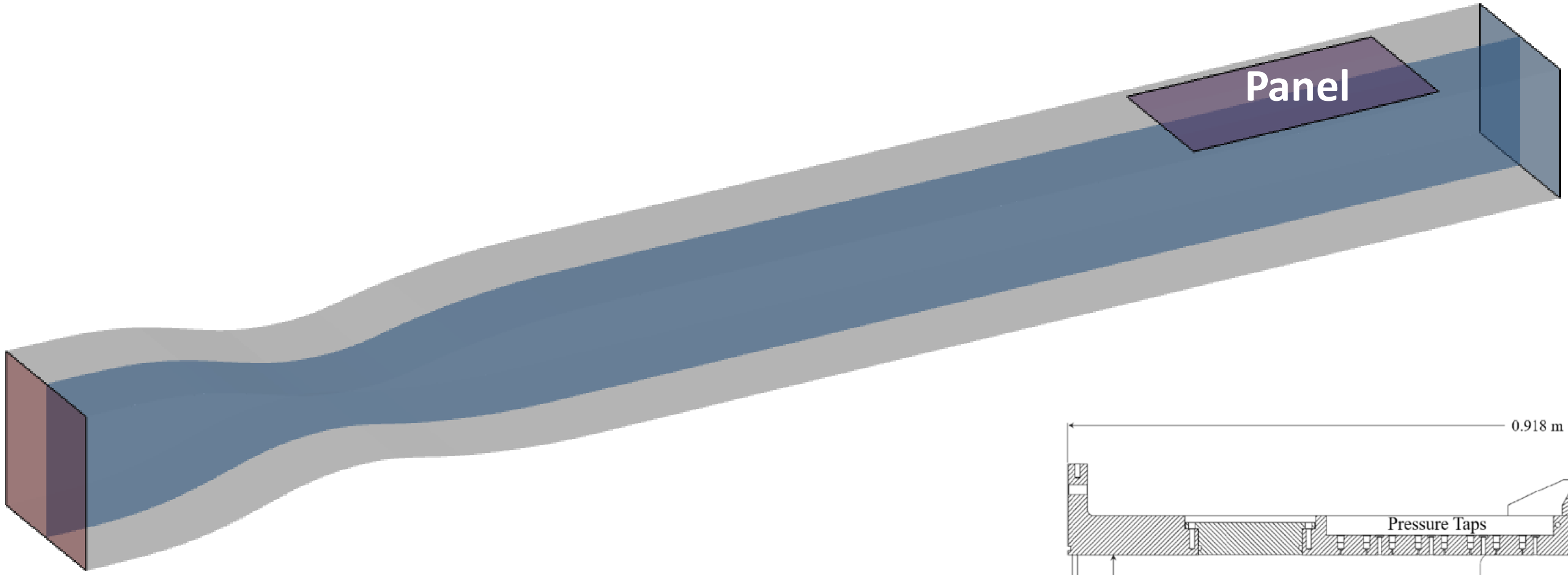
Bret Stanford, Pawel Chwalowski

NASA LaRC, Aeroelasticity Branch

RC19

- Mach 2 tunnel with a flexible panel on the ceiling

Outlet:
Pb/Pref = 0.1



Inlet:
Ptotal/Pref = 6.9
Ttotal/Tref = 1.8

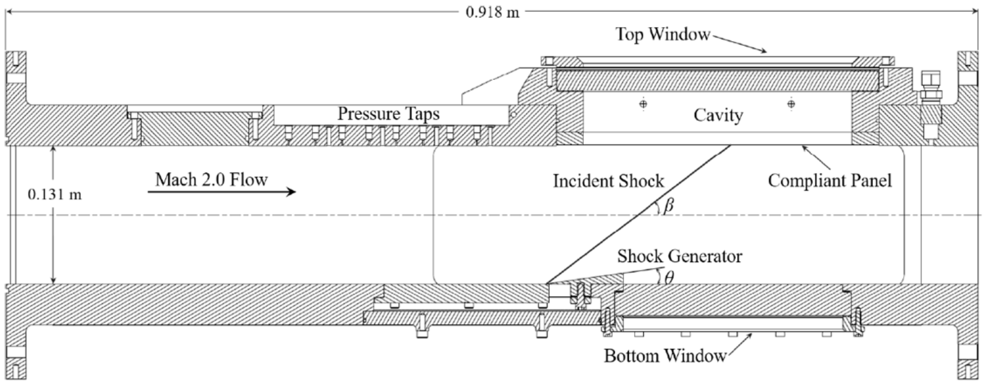
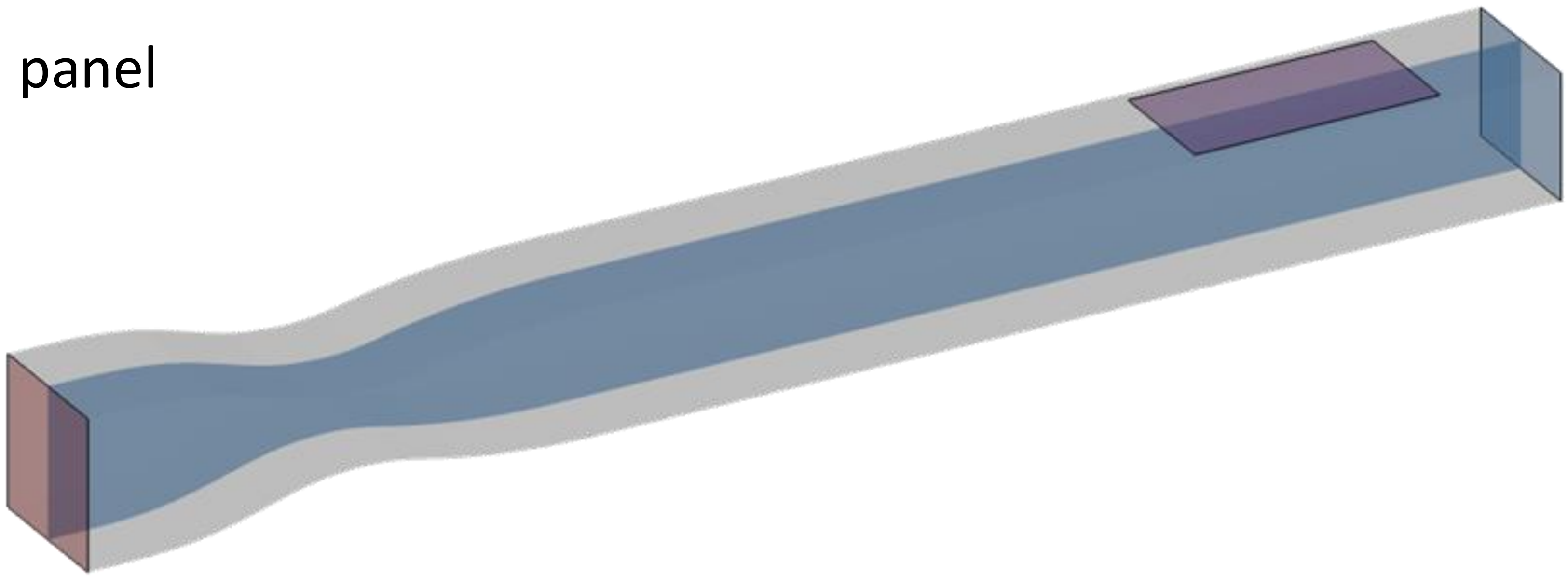


Fig. 1 RC-19 modified test section showing the pressure taps, shock generator, thin panel, and cavity.

RC19

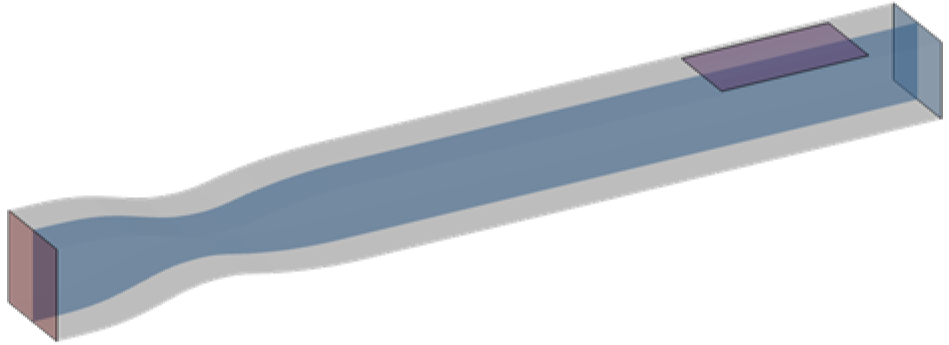
- Four tuning knobs to control response:

1. Panel temperature, ΔT
2. Cavity pressure behind panel
3. Wedge angle
4. In-plane stiffness



Test Cases

- Test case 1: ΔT ≈ 13 K, cavity pressure ≈ 50 kPa, wedge angle = 0 deg.
  - Should cause the panel to flutter, lead to a periodic LCO
- Test case 2: ΔT ≈ 15 K, cavity pressure ≈ 52 kPa, wedge angle = 0 deg.
  - Should lead to chaotic panel vibrations
- Test case 3: ΔT ≈ 13 K, cavity pressure ≈ 68 kPa, wedge angle = 4 deg.
  - Shock impingement on panel from wedge
- We have only attempted cases 1 and 3



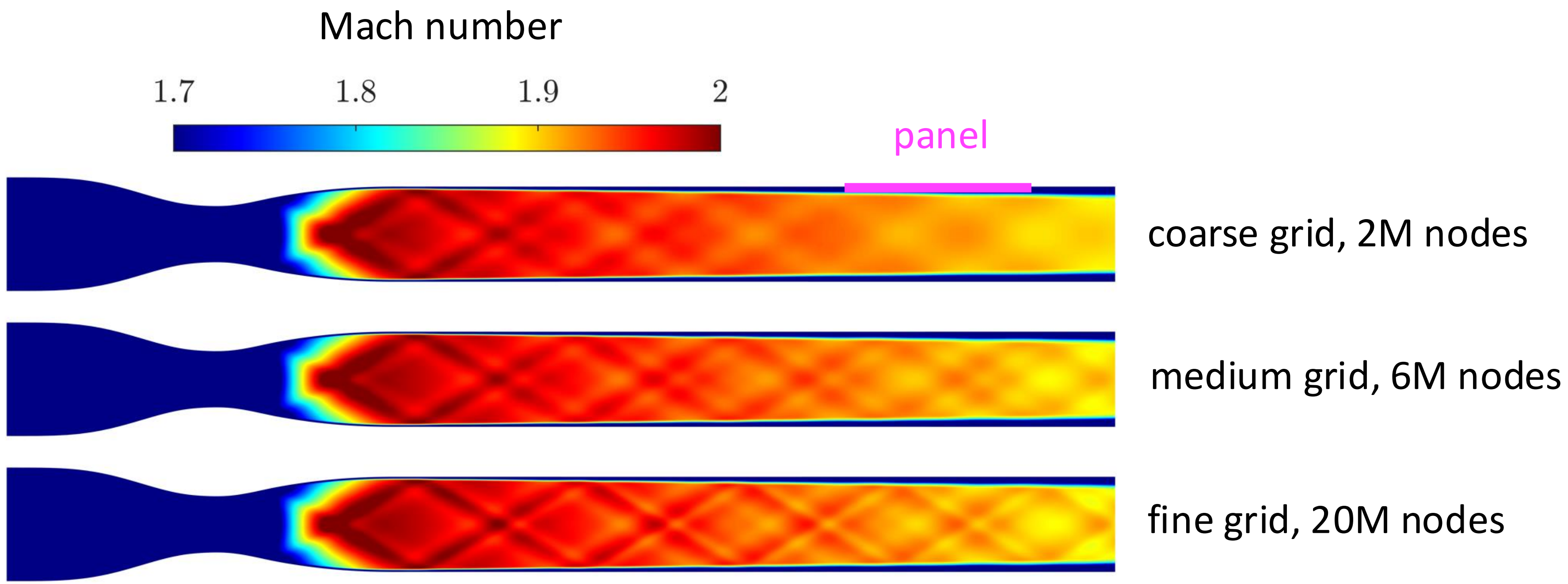
Solver

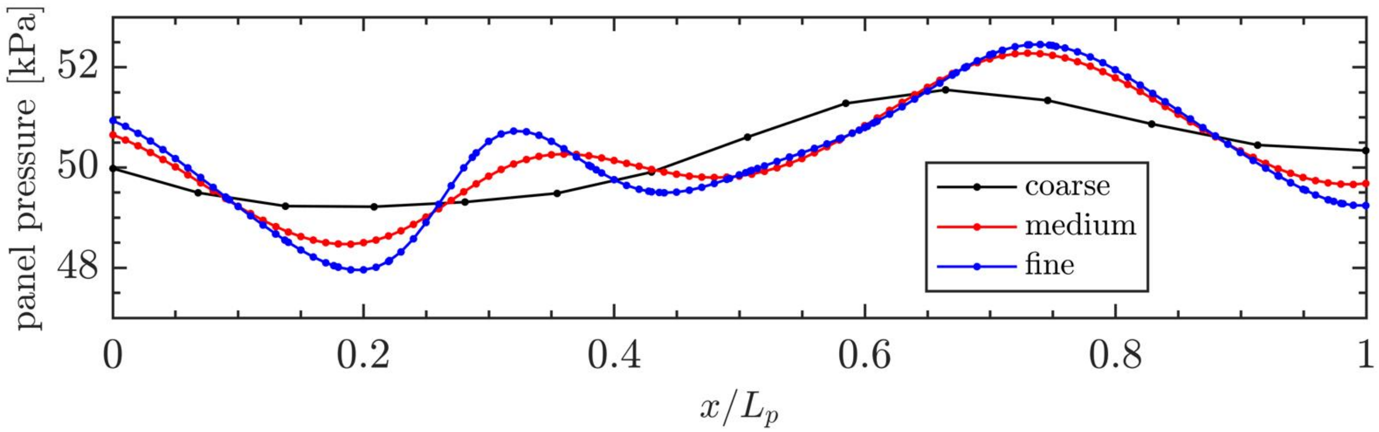
- Aeroelastic coupling computed with FUNtoFEM
- https://github.com/smdogroup/funtofem
- Allows for coupling between NASA's FUN3D solver and an arbitrary finite element model, via python
  - Steady coupling: NLBGS
  - Loose unsteady coupling: one fluid-structure pass per time step
  - Tight unsteady coupling: multiple fluid-structure passes per time step (NLBGS)
- We use loose unsteady coupling:
  - FUN3D: unsteady finite-volume RANS solver with SA
  - FEA: in-house nonlinear shell solver
  - Information transferred between FUN3D and FEA via MELD

FUN3D Details

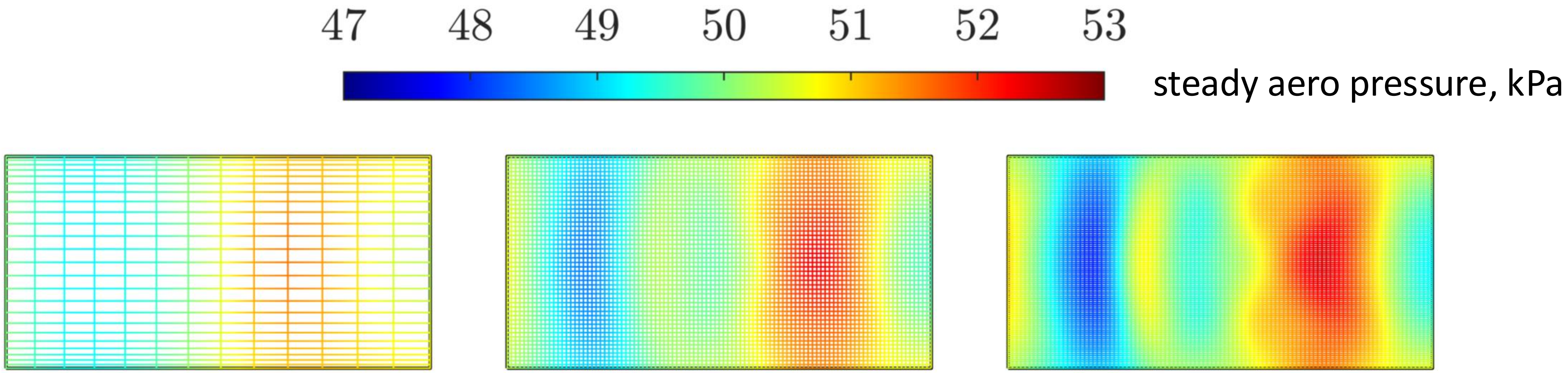
- All of our manually-built FUN3D meshes have a surface y+ at the panel about equal to 0.4
  - For the case with the wedge, a y+ of 2 was needed to keep the flow solver from crashing
- We have also used a Heldenmesh-based mesh adaptation process for some cases
  - y+ for these meshes is ~0.5
- Nondimensional time step is 2.5E-4 (8.5E-7 seconds)

Steady Flow Fields, Rigid Panel, No Wedge





Steady Pressures on Rigid Panel



coarse grid, 2M nodes | medium grid, 6M nodes | fine grid, 20M nodes

- If cavity pressure is 50 kPa, then mean steady Δp is nearly 0
  - Negative 2-3 kPa near LE, positive 2-3 kPa near TE

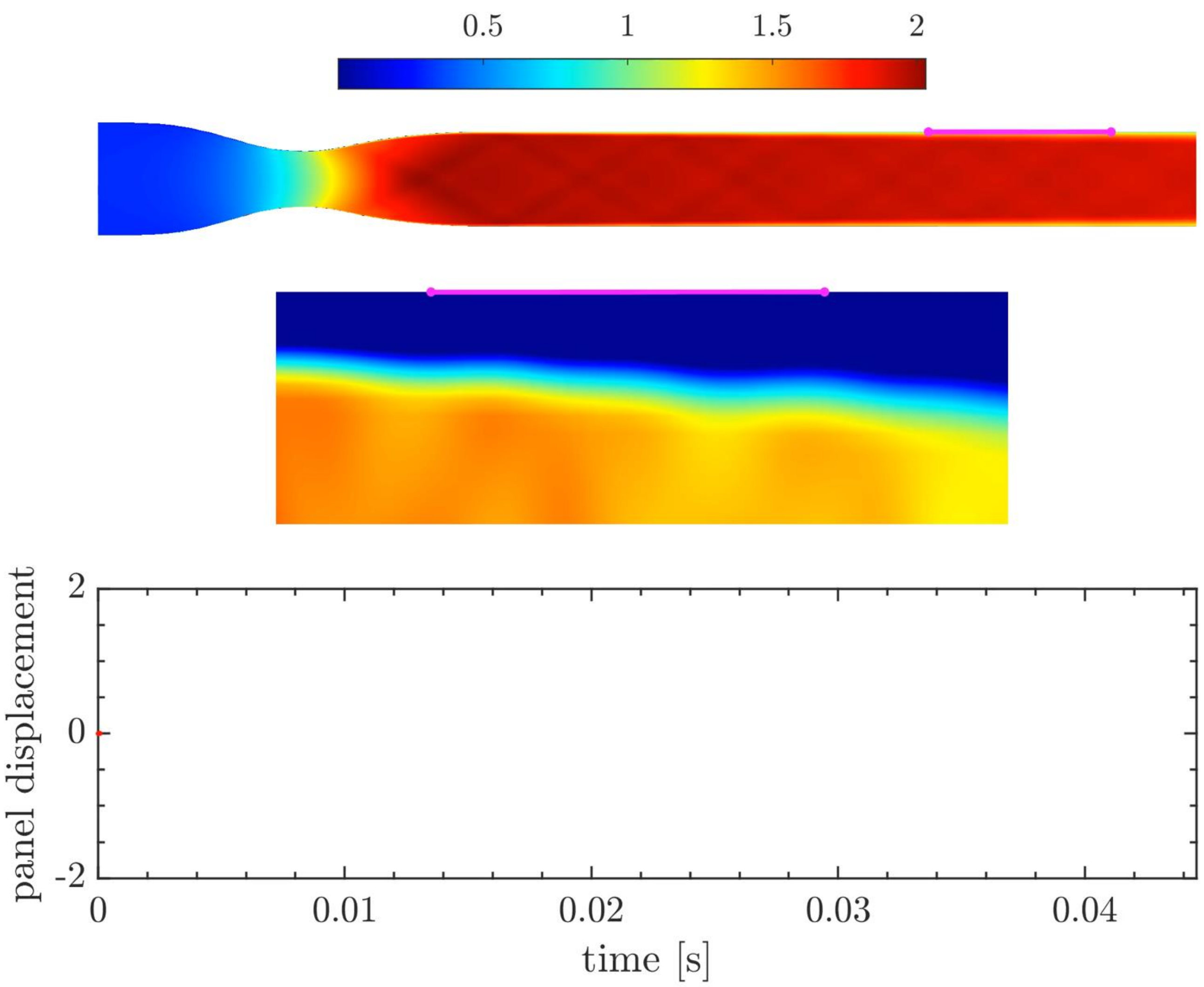
Boundary Layer Thickness

- Our computed boundary layer at the panel is ~13 mm thick
- The experimentally-measured boundary layer is closer to 9 mm thick

- A potential reason: we are modeling the entire setup (nozzle + test section) as turbulent
  - In reality, the flow will start out as laminar, and transition at some point in the nozzle (?)

- Does it matter?
  - Comparison with some of AFRL's CFL3D results (where the nozzle is omitted, and the correct BL thickness is computed), shows we are over-predicting the peaks and valleys of the local pressure distribution over the panel
  - Those peaks and valleys add extra load onto the panel

Test Case 1 Results

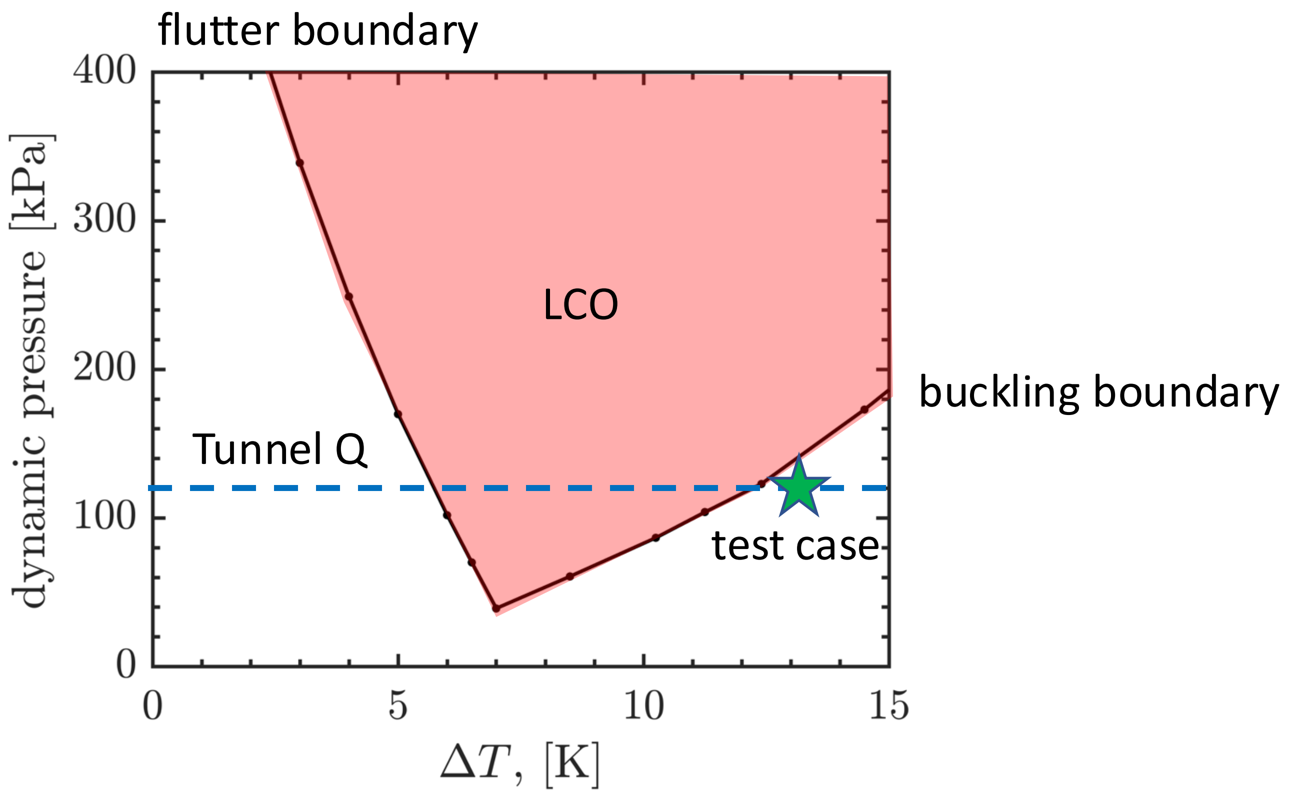


Test Case 1 Results

- The experiment shows a clean periodic LCO, but our numerical results show that the panel settles into a deformed steady-state
- Why?
  - We are assuming a spatially-uniform temperature over the panel, which is unlikely to be true
  - We are also assuming that the in-plane supports on the panel are rigid
- Use a simple piston theory model to gain some insight

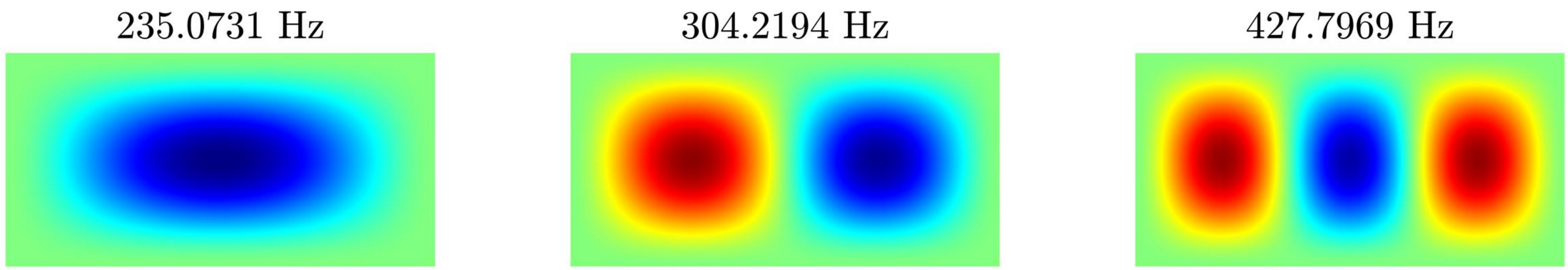
Piston Theory Aerodynamics

- Use PTA to better understand the parameter space:
  - Dynamic pressure stability boundaries via changes in panel temperature
  - ***Assumes no steady pre-load on panel***



Accuracy of PTA for this Case?

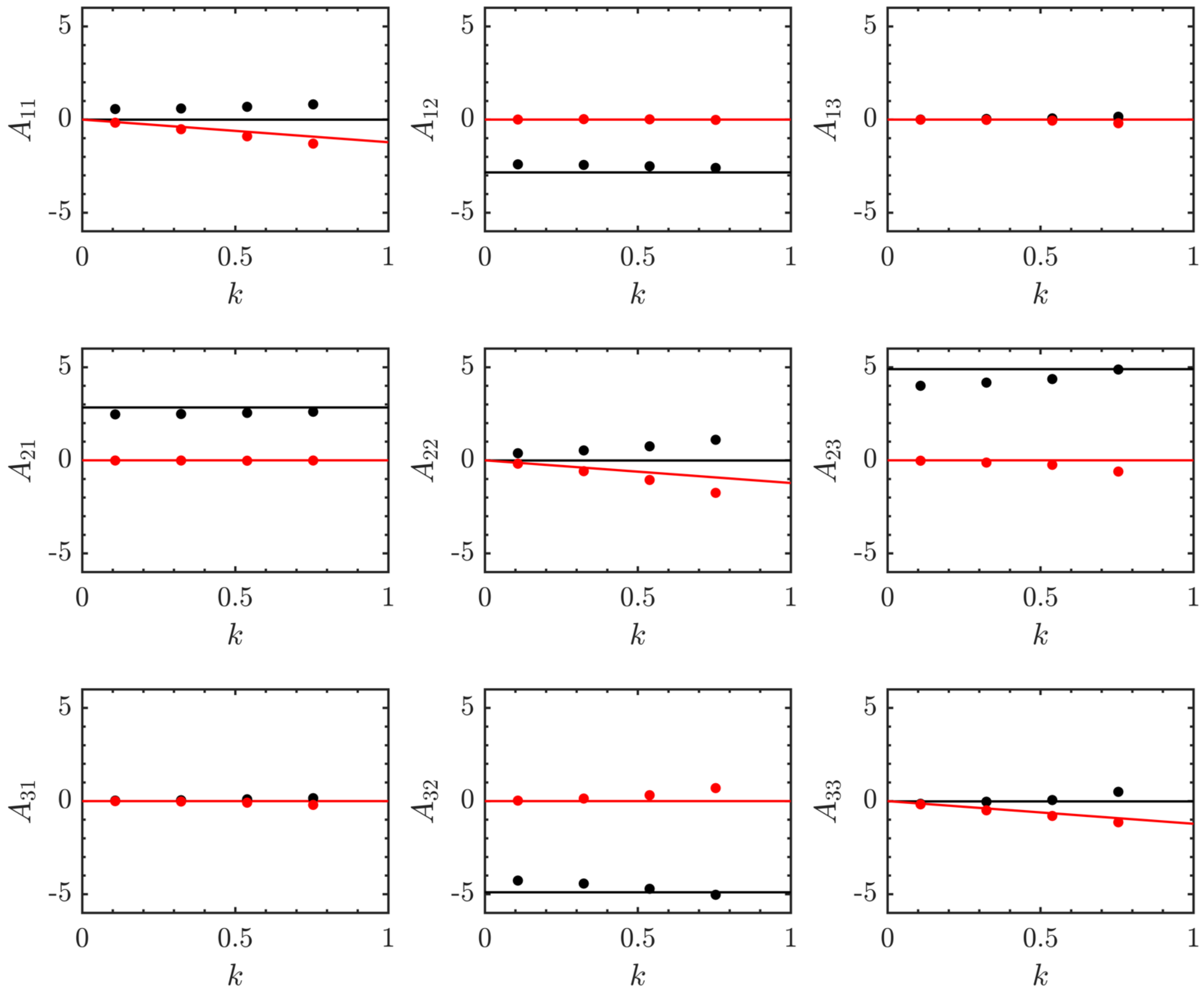
- Use Linearized Frequency Domain (LFD) to compare FUN3D Generalized Aerodynamics Forces (GAFs) to piston theory GAFs
- Compute GAFs for the first 25 modes, but only showing results for the first 3 modes



measured pre-installed frequencies are 242, 302, and 418 Hz

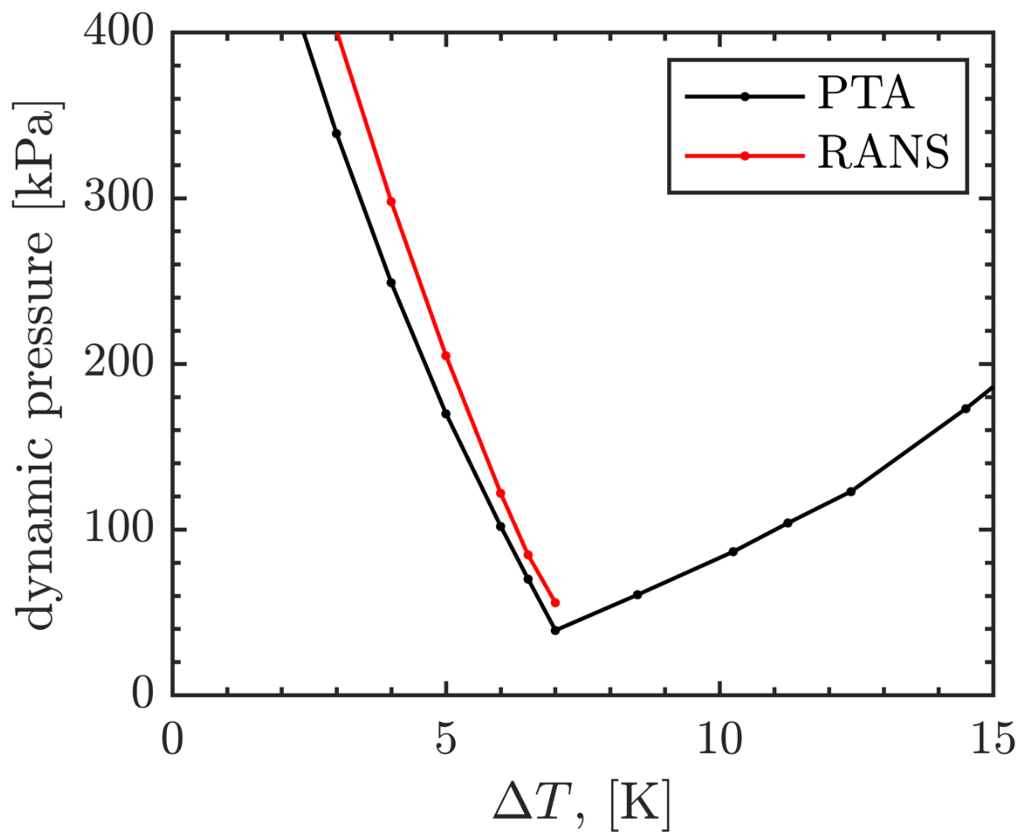
GAFs

- Black: real
- Red: imaginary
- Lines: piston theory
- Dots: FUN3D



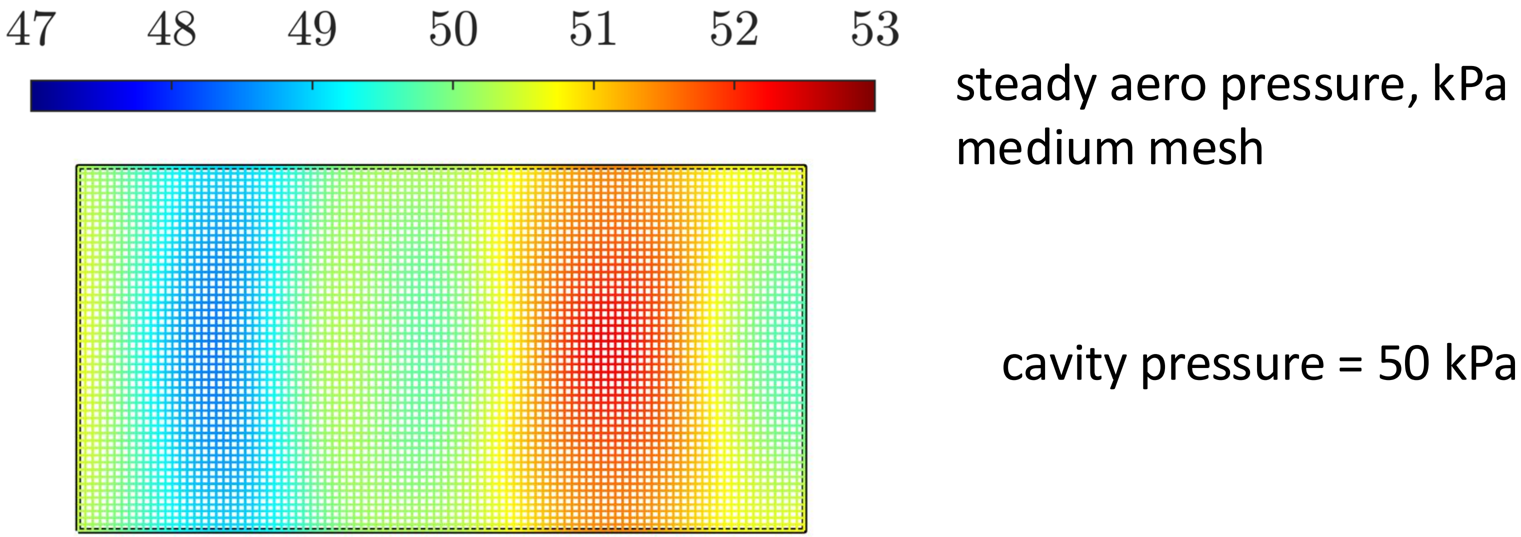
Linearized Flutter Boundaries

- PTA- and FUN3D-based linearized flutter boundaries agree well
  - ***Assumes no steady pre-load on panel***



Steady Pressures on Panel

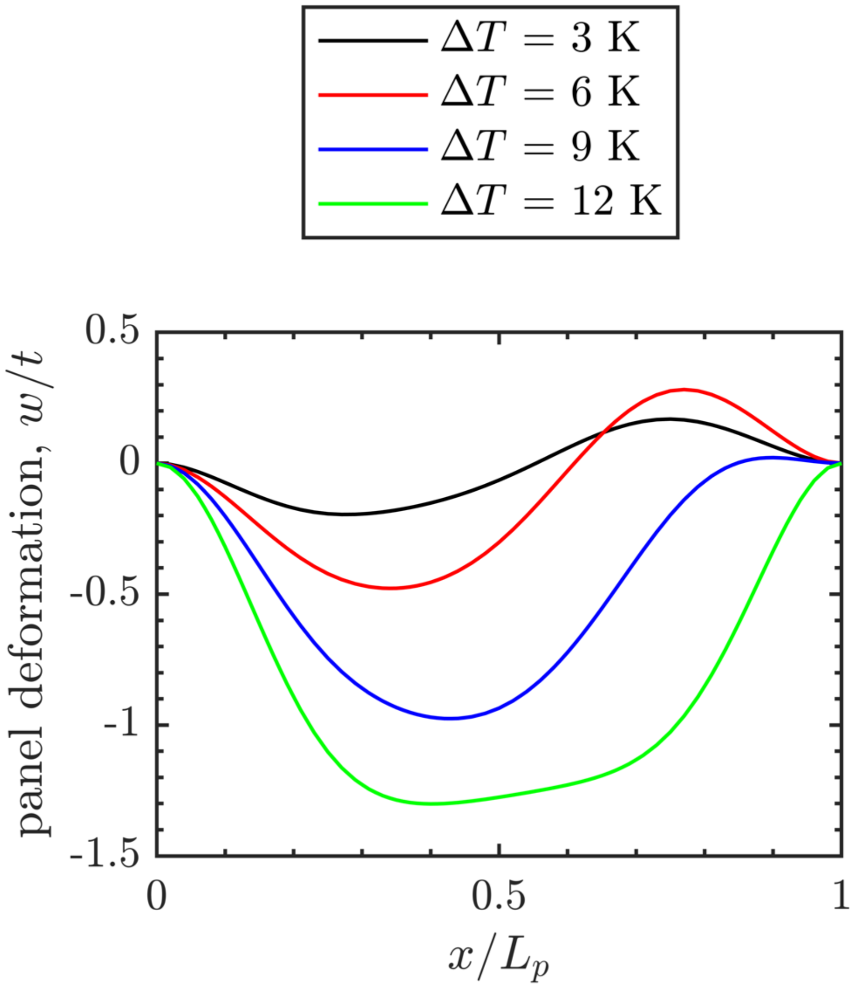
- Mean delta-pressure over the panel is ~0, but there are nonzero delta-pressures near the LE and TE, due to the diamond-shape shock in the test section



cavity pressure = 50 kPa

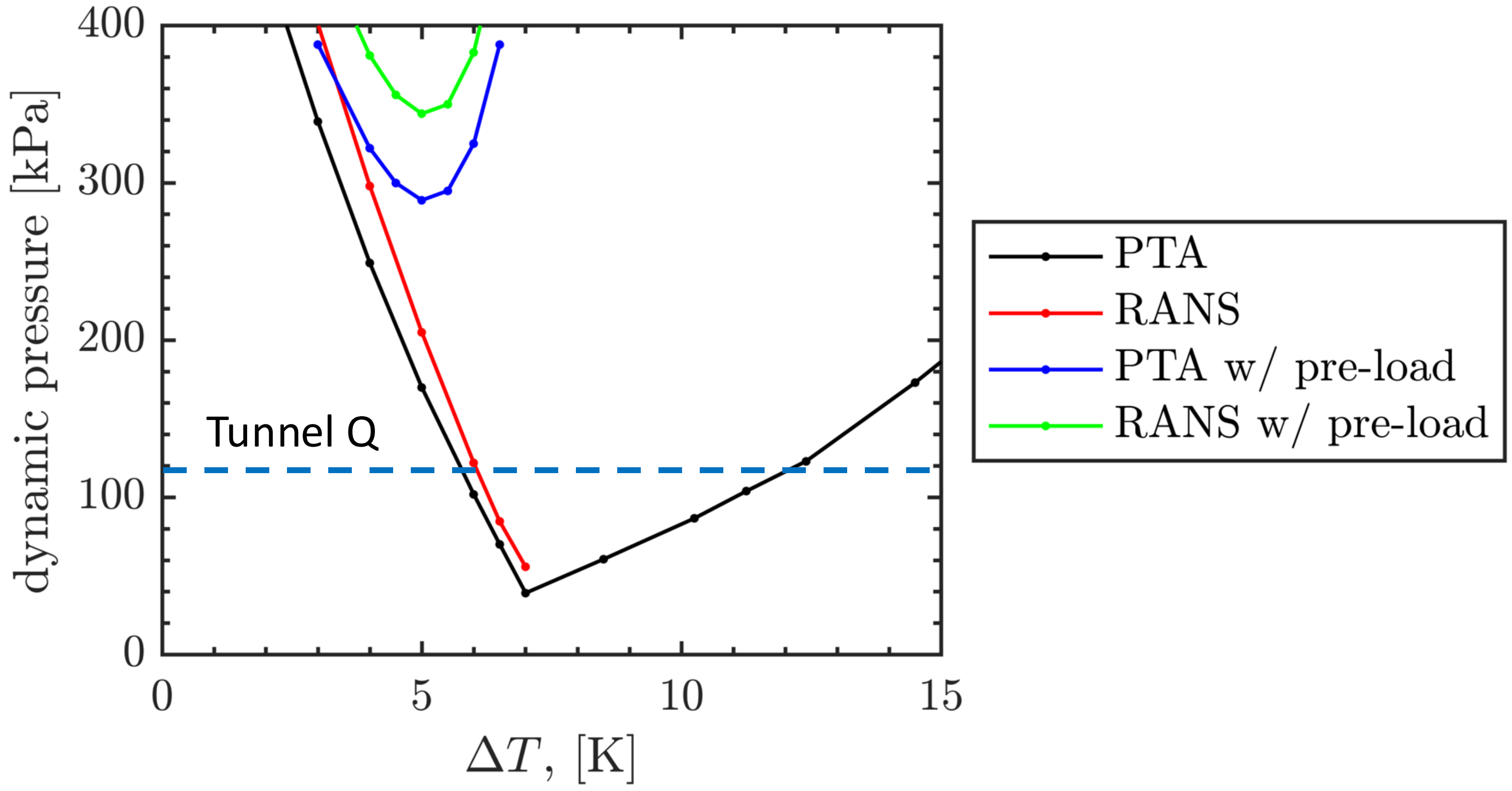
Steady Deformations of the Panel

- Small ΔT values add compressive loads into the panel
  - Panel deforms into an S-shape due to the steady aero load
- But increased ΔT causes the panel to bulge downwards, actually adding tensile loads into the panel
  - Compressive stresses are largest near 6 K
- The tensile loads at higher ΔT will stiffen the panel



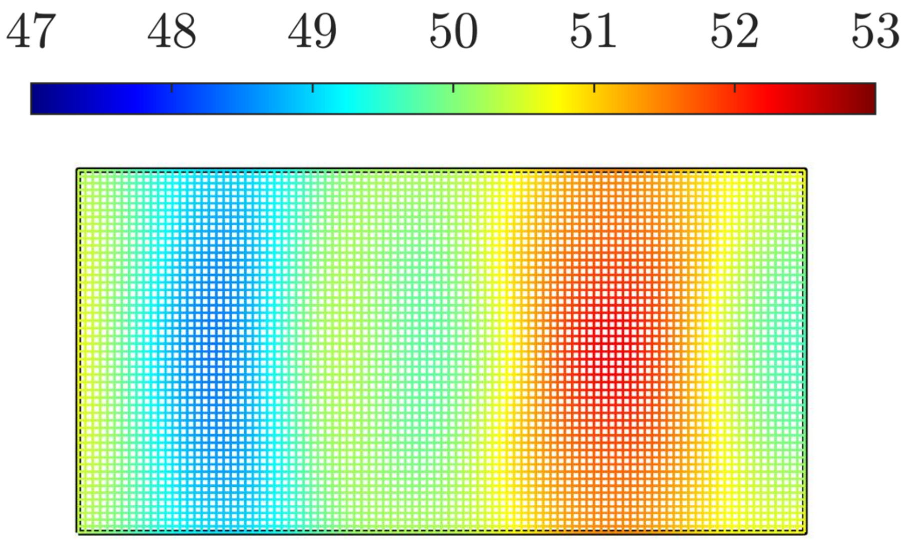
Linearized Flutter Boundaries, Accounting for Preload

- The large tensile loads (stiffening) above 5-6 K are quenching the oscillatory dynamics



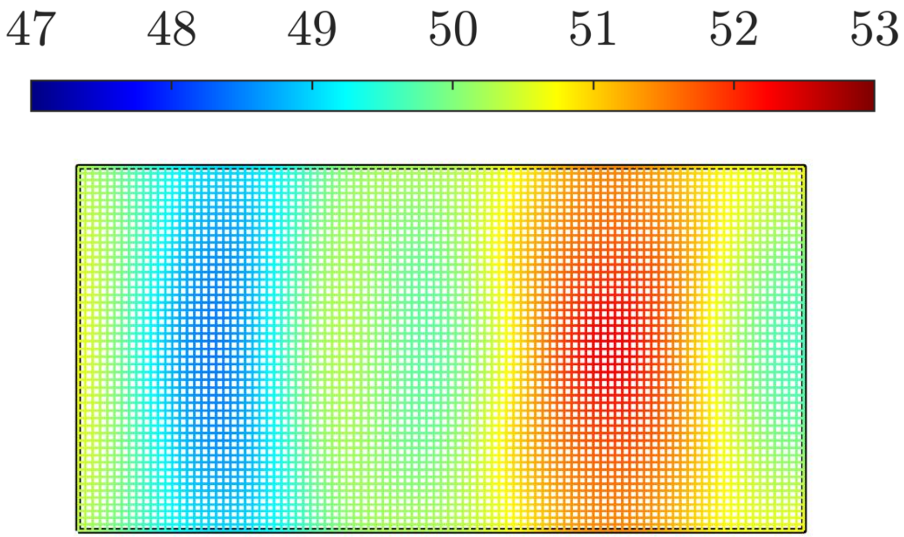
Effect of Static Pressure Differential

- If we decrease the valley-to-peak static pressures on the panel, this will give us the panel oscillations that we want
  - i.e., decrease the strength of the diamond-shaped shock
- Could potentially do this by omitting the nozzle from the model
- Or, for now, we can numerically remove those steady pressures



FunToFem Simulation with Fake Cavity Pressures

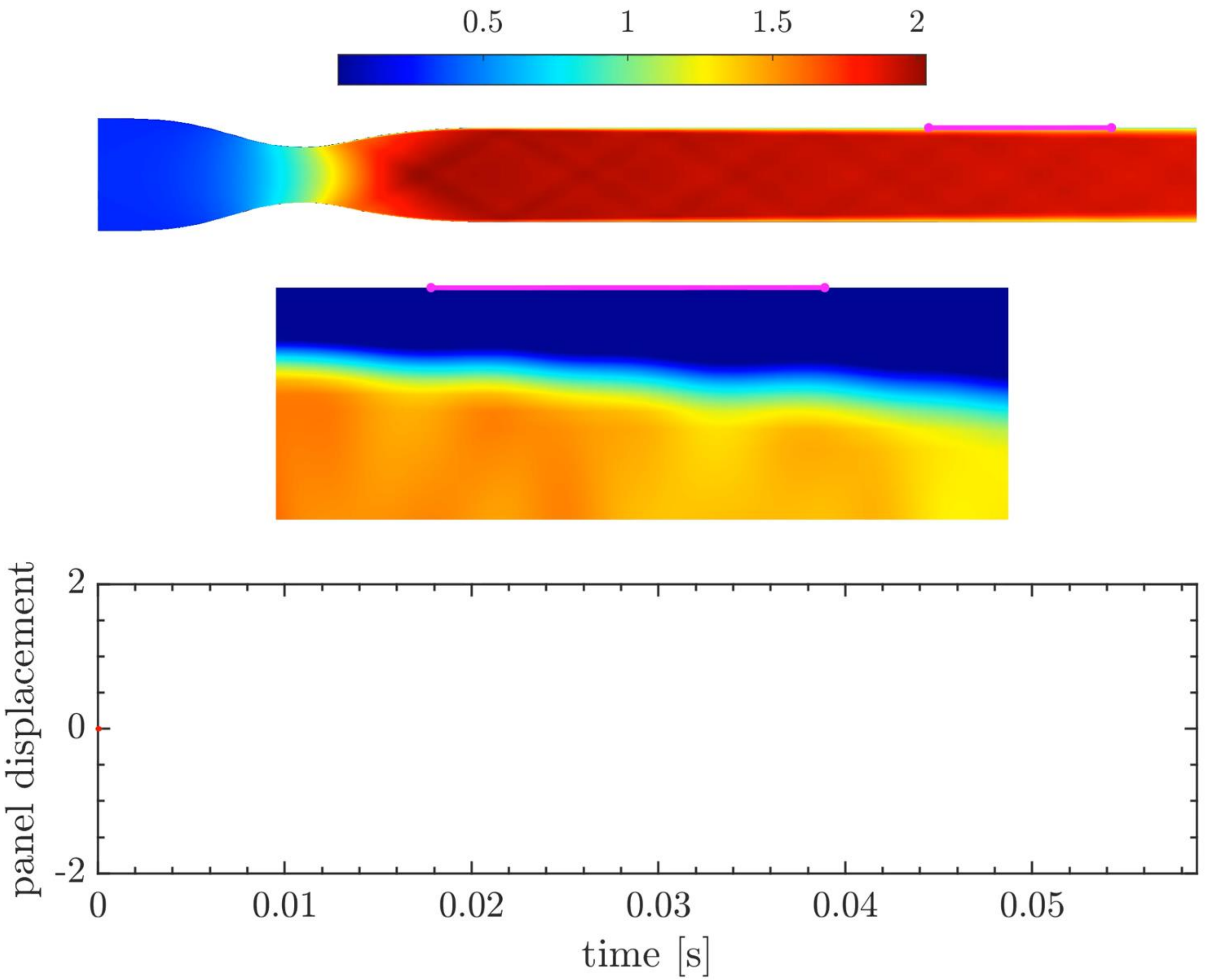
- Remove the preload in FunToFem by applying a cavity pressure exactly equal-and-opposite to the steady aerodynamic pressures
  - Now the steady delta-pressure is exactly equal to 0, everywhere
  - The only pressures on the panel are unsteady aerodynamic pressures



steady aero pressure, kPa
medium mesh

Panel LCO

- Extreme case:
  - Numerically set the steady delta-pressure over the panel exactly equal to 0, everywhere
  - The only pressures on the panel are unsteady aerodynamic pressures

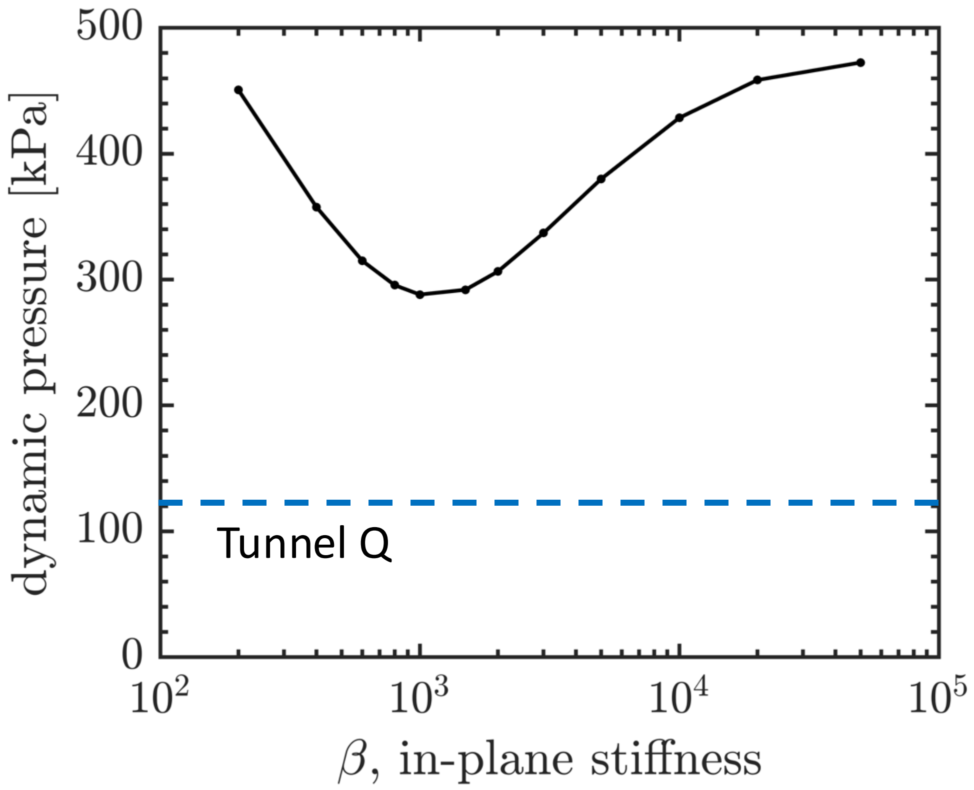


Panel LCO

- Can only obtain the correct result if we ignore the steady aero pressures from the diamond-shaped shock
  - Otherwise, those steady pressures impart large preloads on the panel, increasing flutter Q outside the tunnel envelope
  - If the steady pressures were **nearly-uniform**, we could tweak the cavity pressure to counteract them, and still get the panel to flutter

In-Plane Stiffness

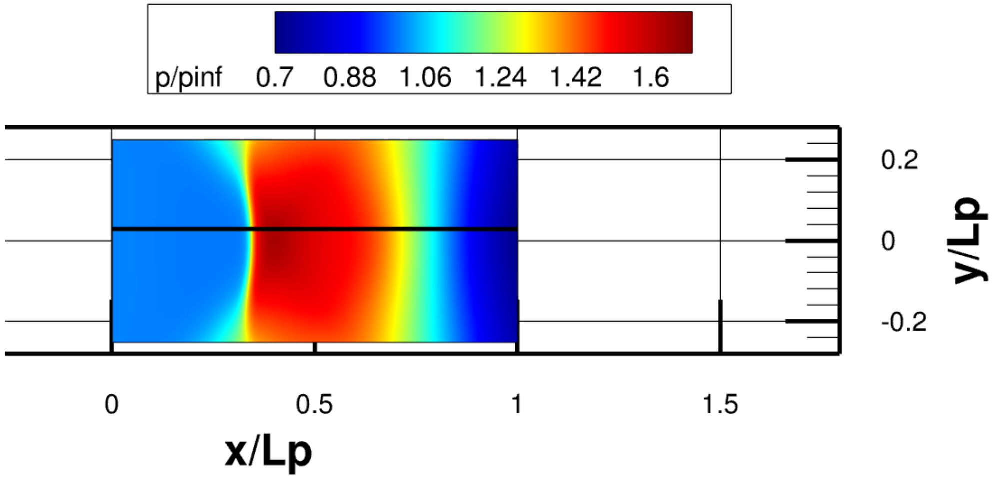
- Modeling the in-plane stiffness as rigid, but there may be some flexibility here
- If we lowered this stiffness, would it help obtain flutter in the tunnel envelope?

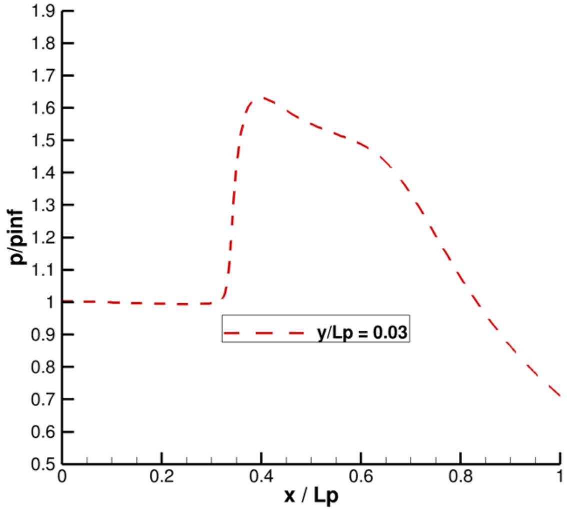


- $\Delta T = 7$ K
- Decreasing β helps at first, b/c impact of pre-load is weakened
- But decreasing β too much causes flutter Q to increase again, b/c thermal loads decrease

Test Case 3

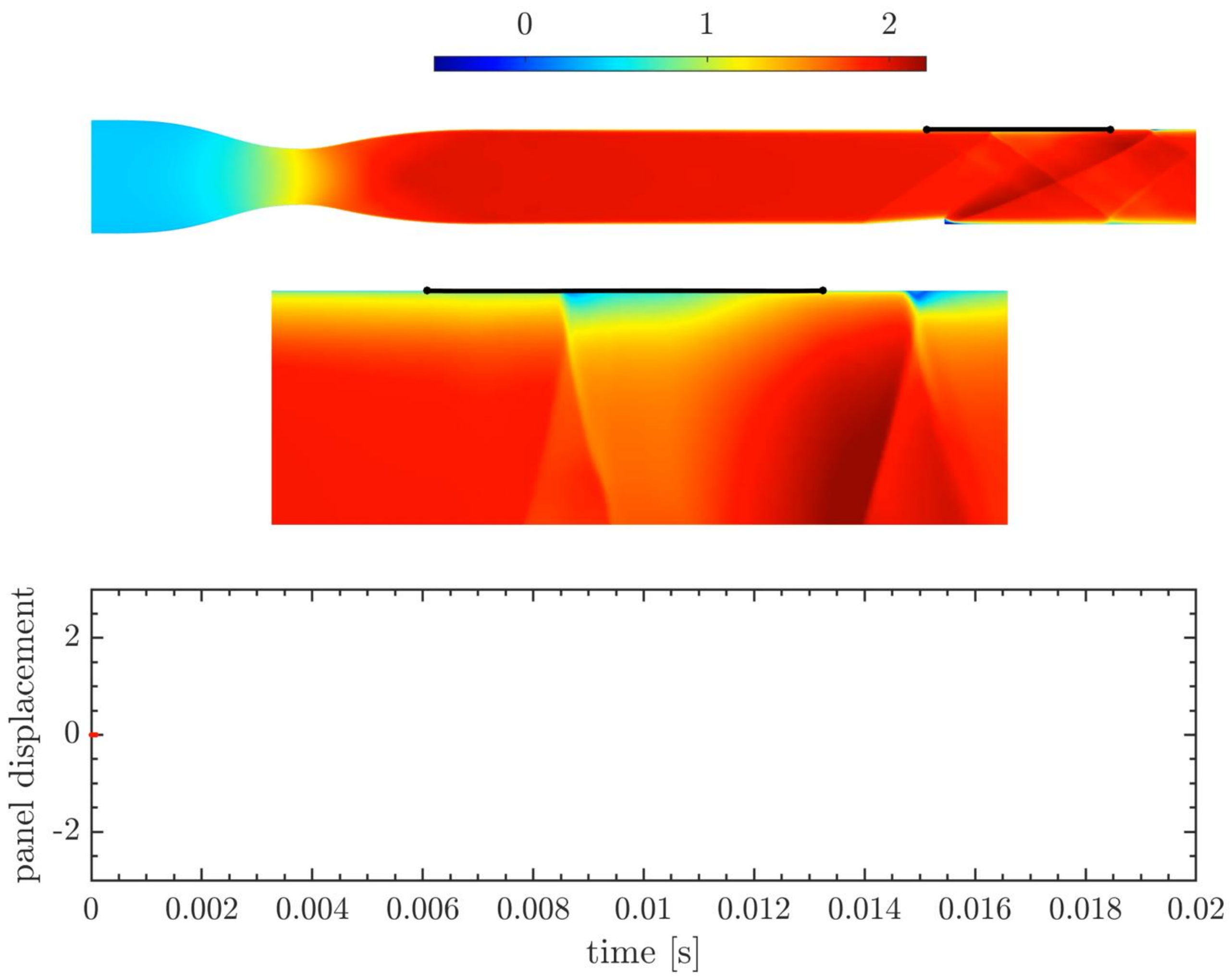
- Steady flows over the rigid panel, with a 4 deg. wedge angle, could be obtained with a surface y+ of 0.4



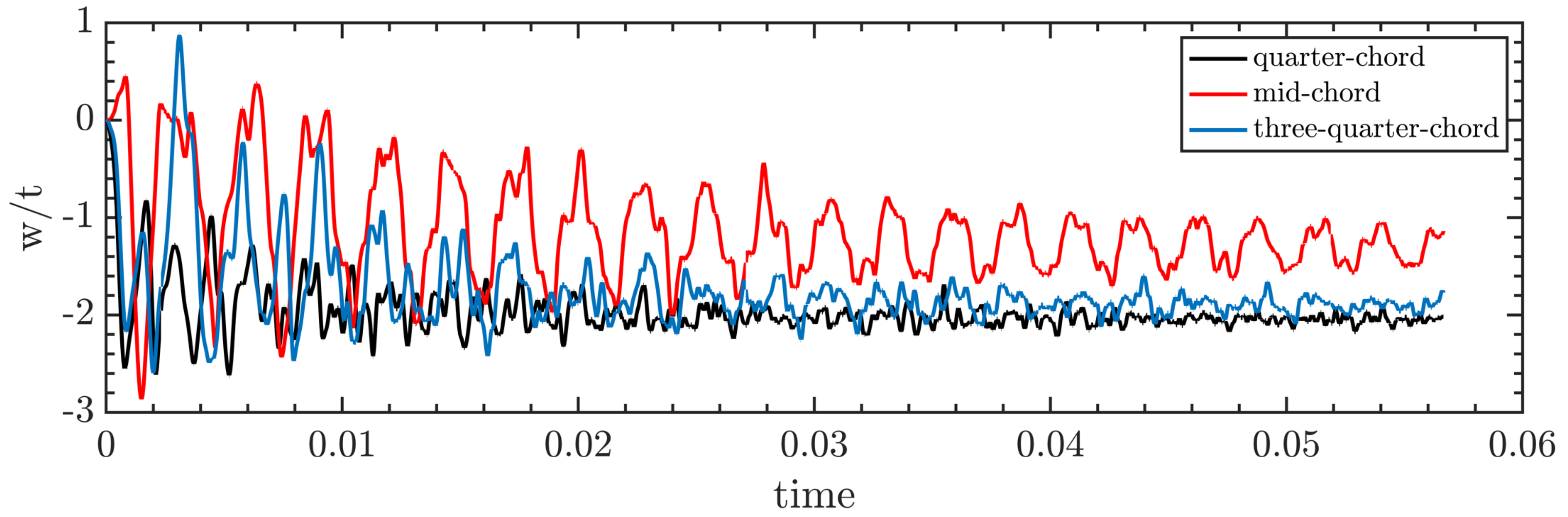


- But for unsteady flows over the deforming panel, this mesh would crash
  - A mesh with a higher y+ (2.0) does work, however

Test Case 3 Results



Test Case 3 Results



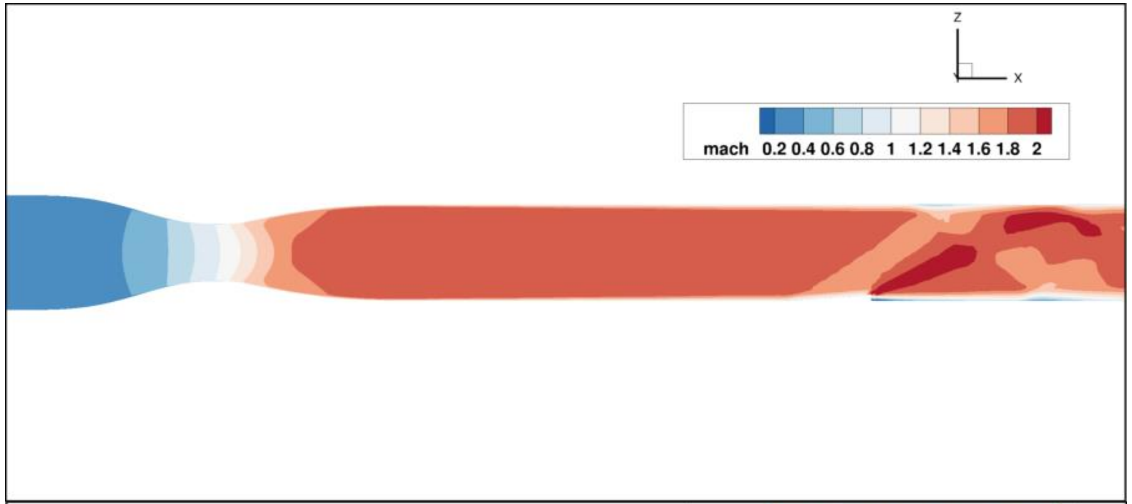
- Panel gradually settles into a W-shape
  - Panel mostly deforms downward, due to the high cavity pressure
  - But the mid-part of the panel inflects upward, a little, from the shock
- Like test case 1, this is the wrong answer:
  - Experimental results show a chaotic self-standing motion

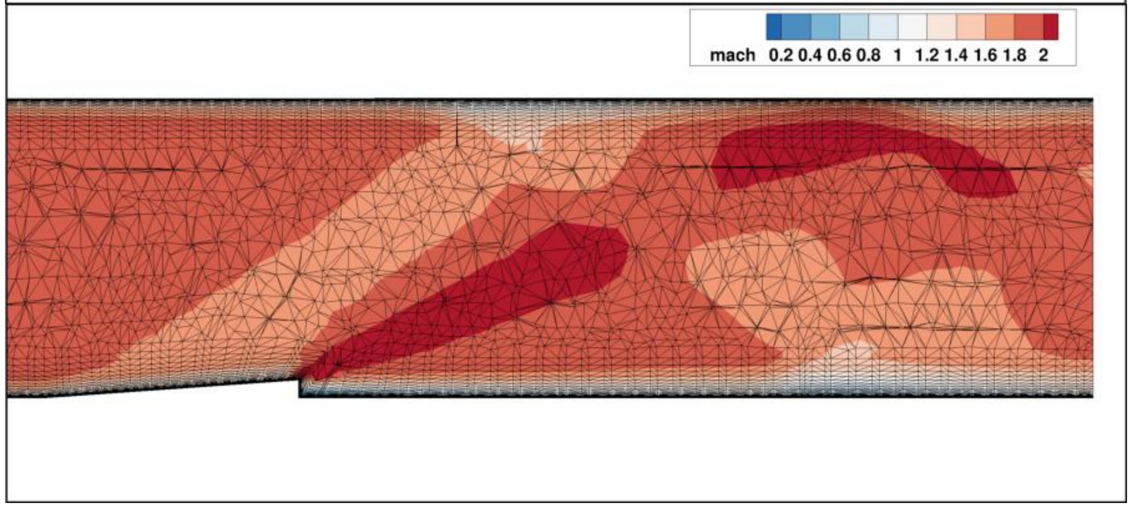
Mesh Adaptation

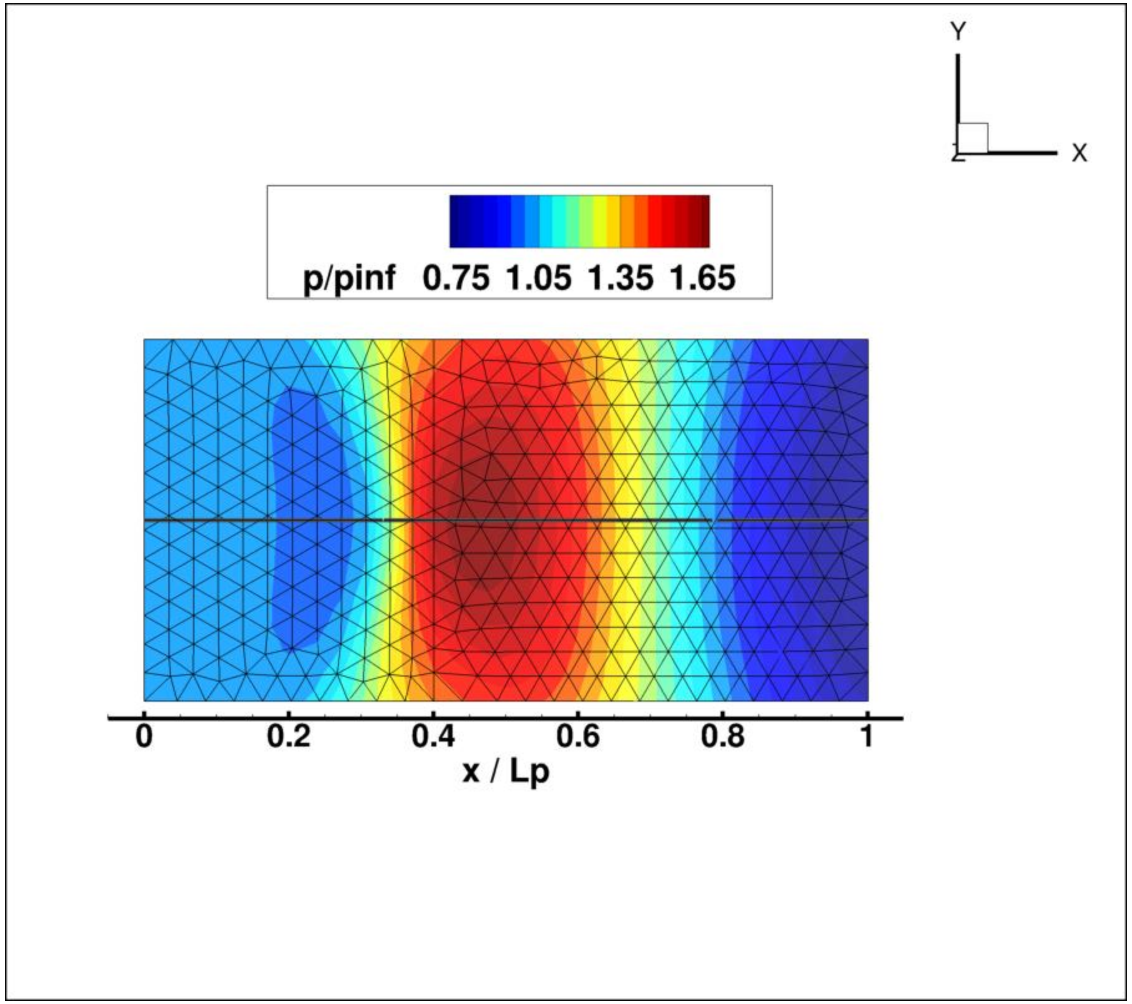
- Adaptation process developed by Steve Massey (NASA Aeroelasticity Branch)
- A hybrid approach that combines refine and Heldenmesh:
  1. The open source ***refine*** tool (**github.com/nasa/refine**) to create anisotropic sources based on a metric field
  2. ***Heldenmesh*** creates meshes based on those sources

Test Case 3 Mesh Adaptation (Rigid)

Mesh size: 460705

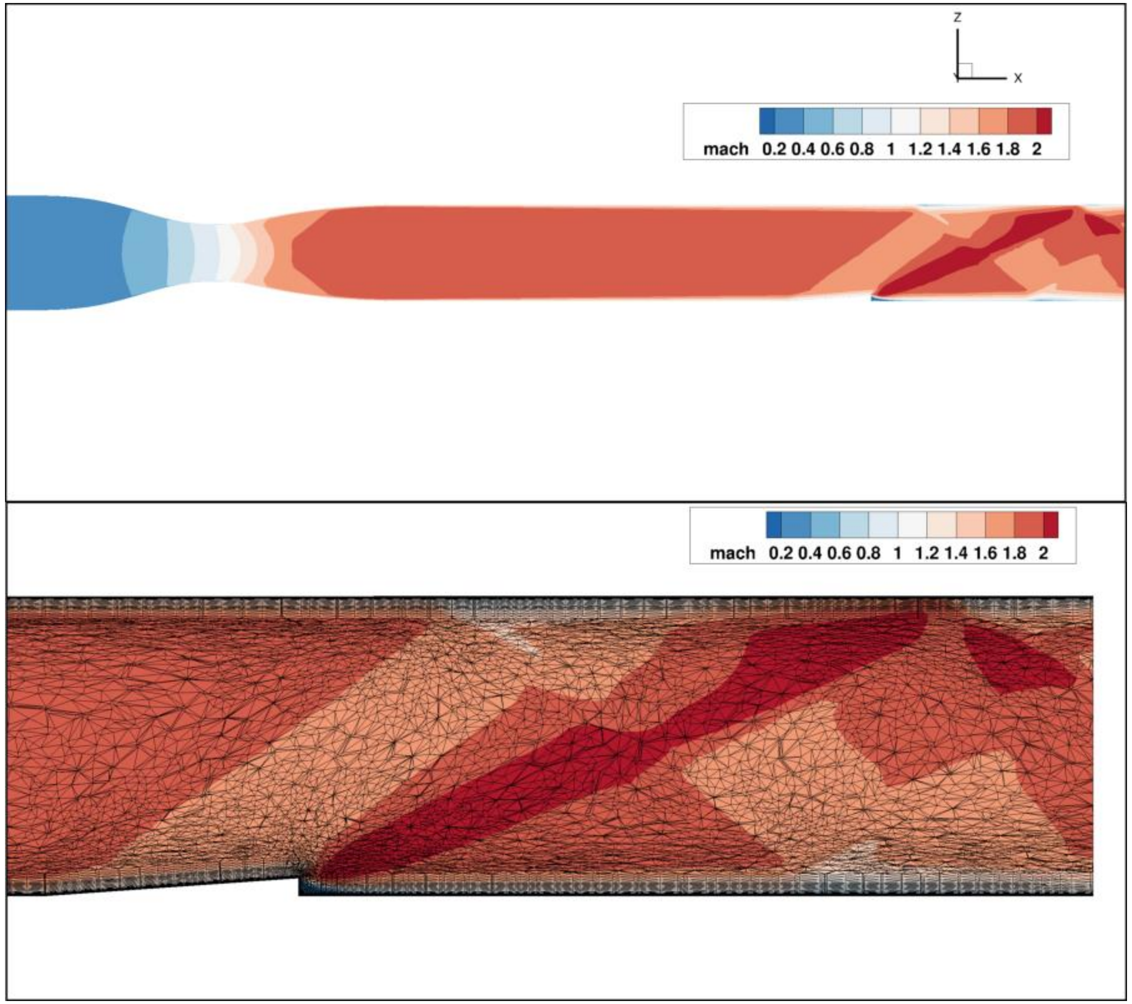


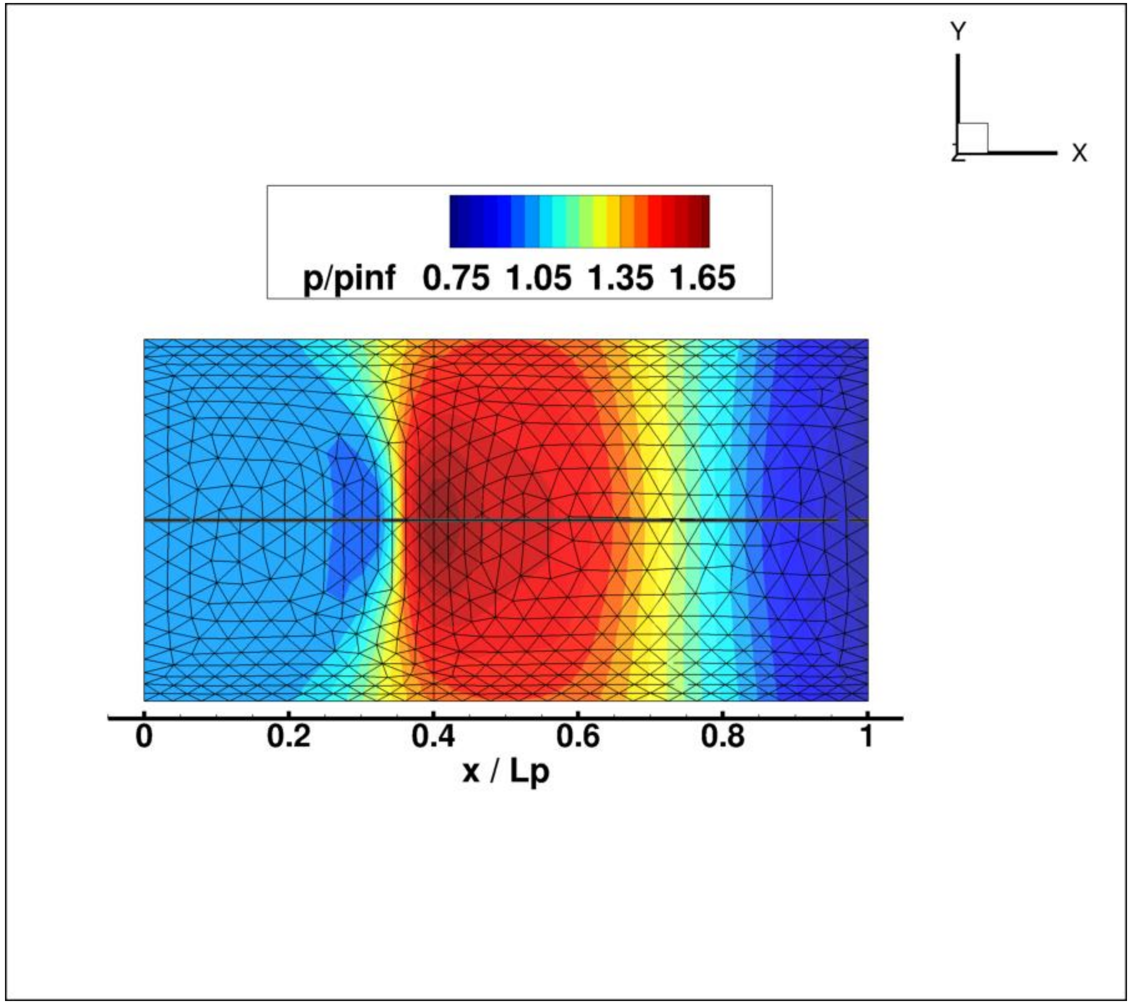




Test Case 3 Mesh Adaptation (Rigid)

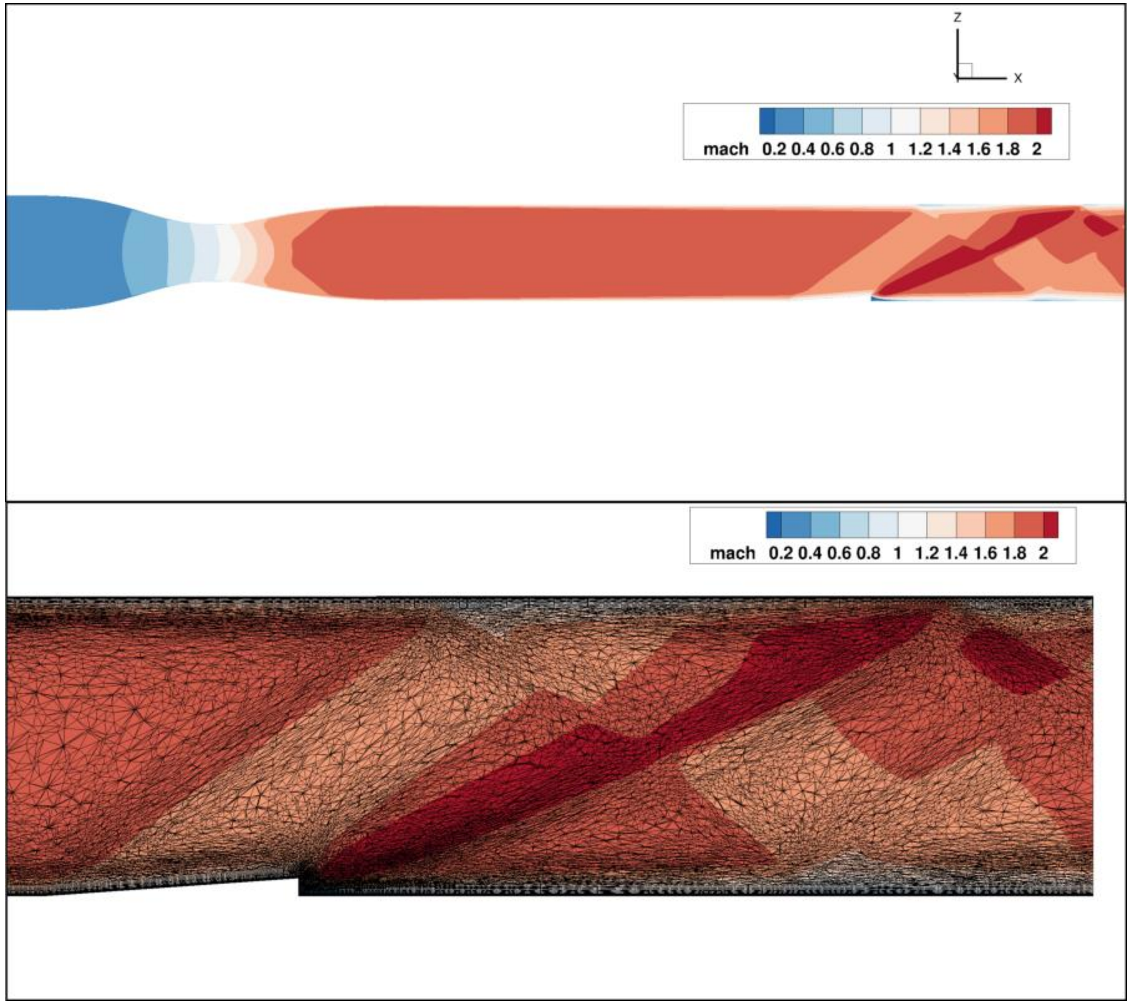
Mesh size: 1139696

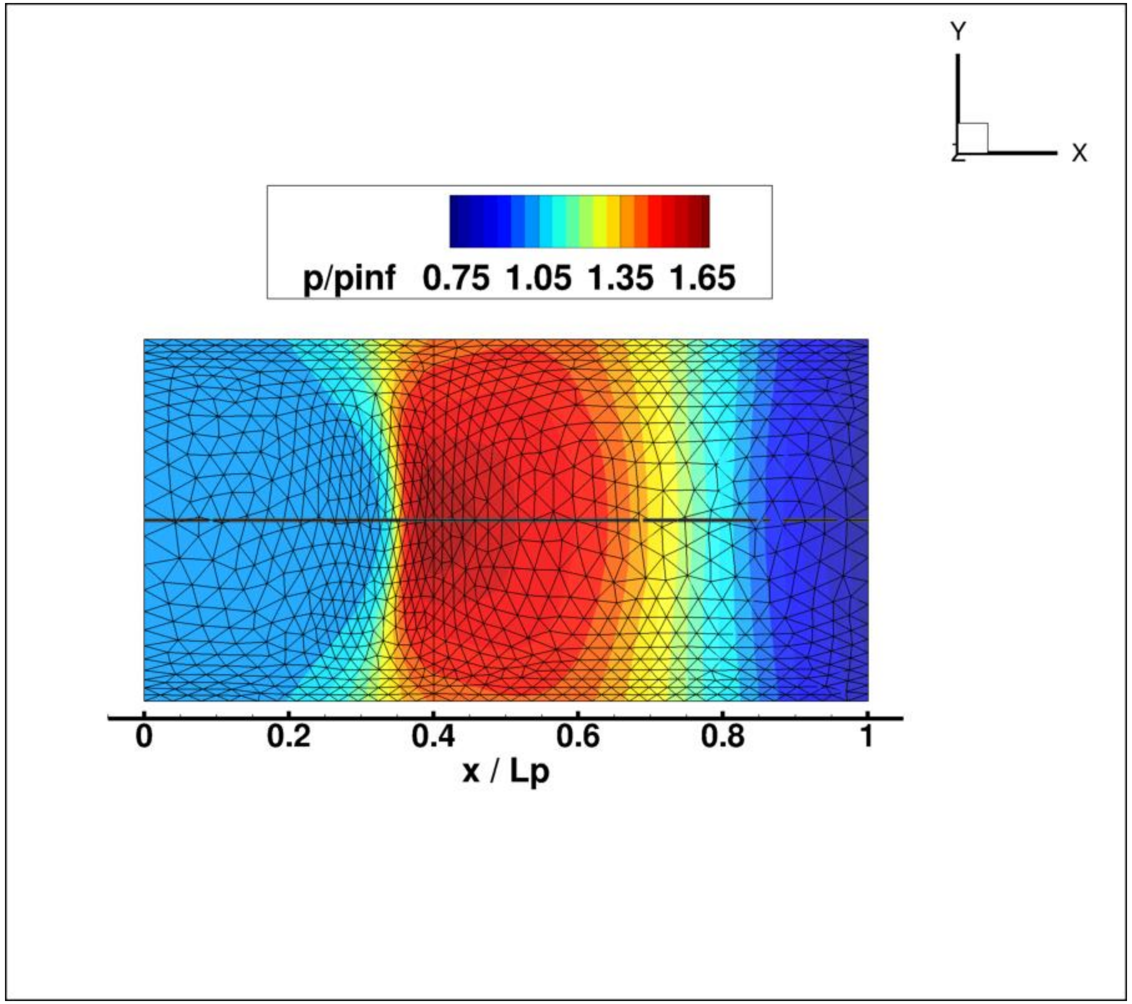




Test Case 3 Mesh Adaptation (Rigid)

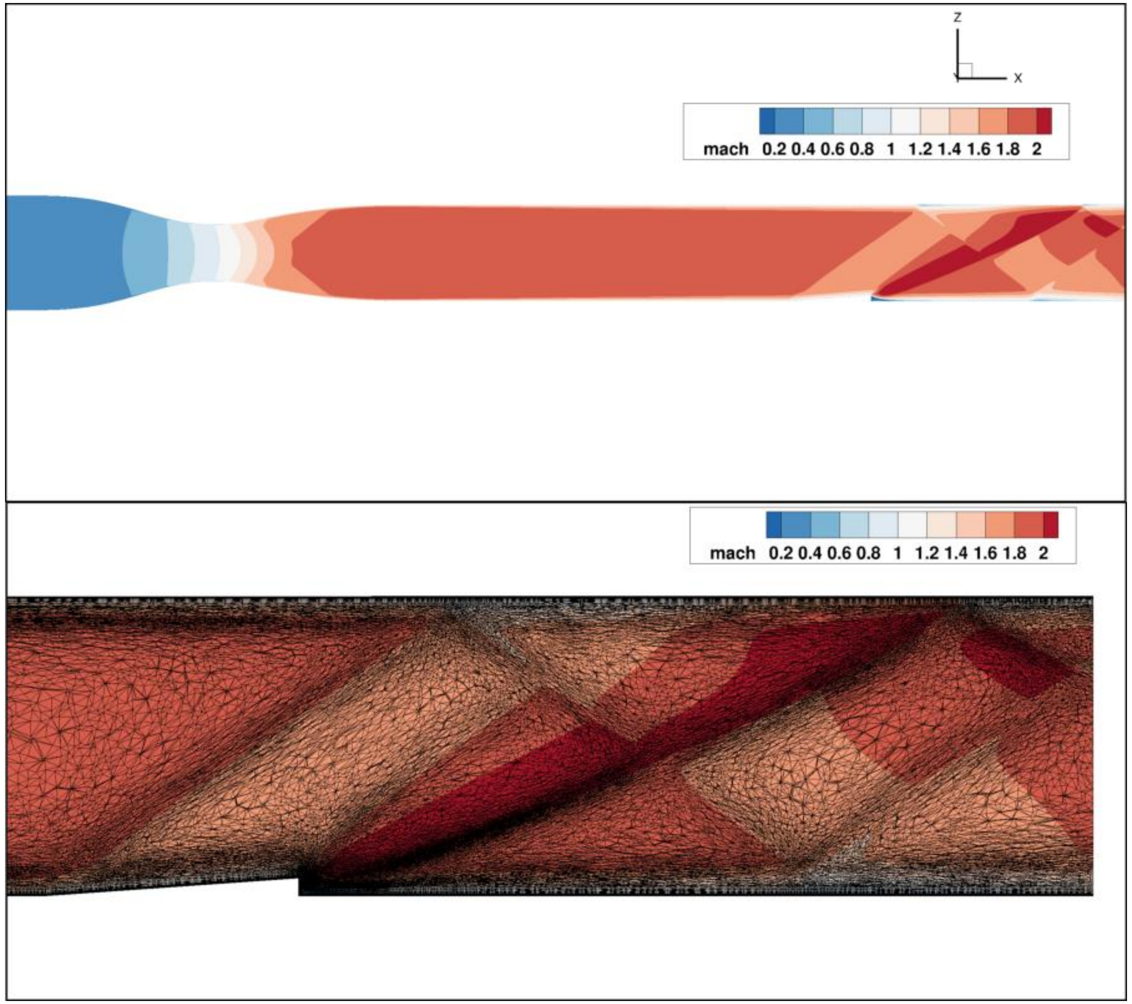
Mesh size: 1786264

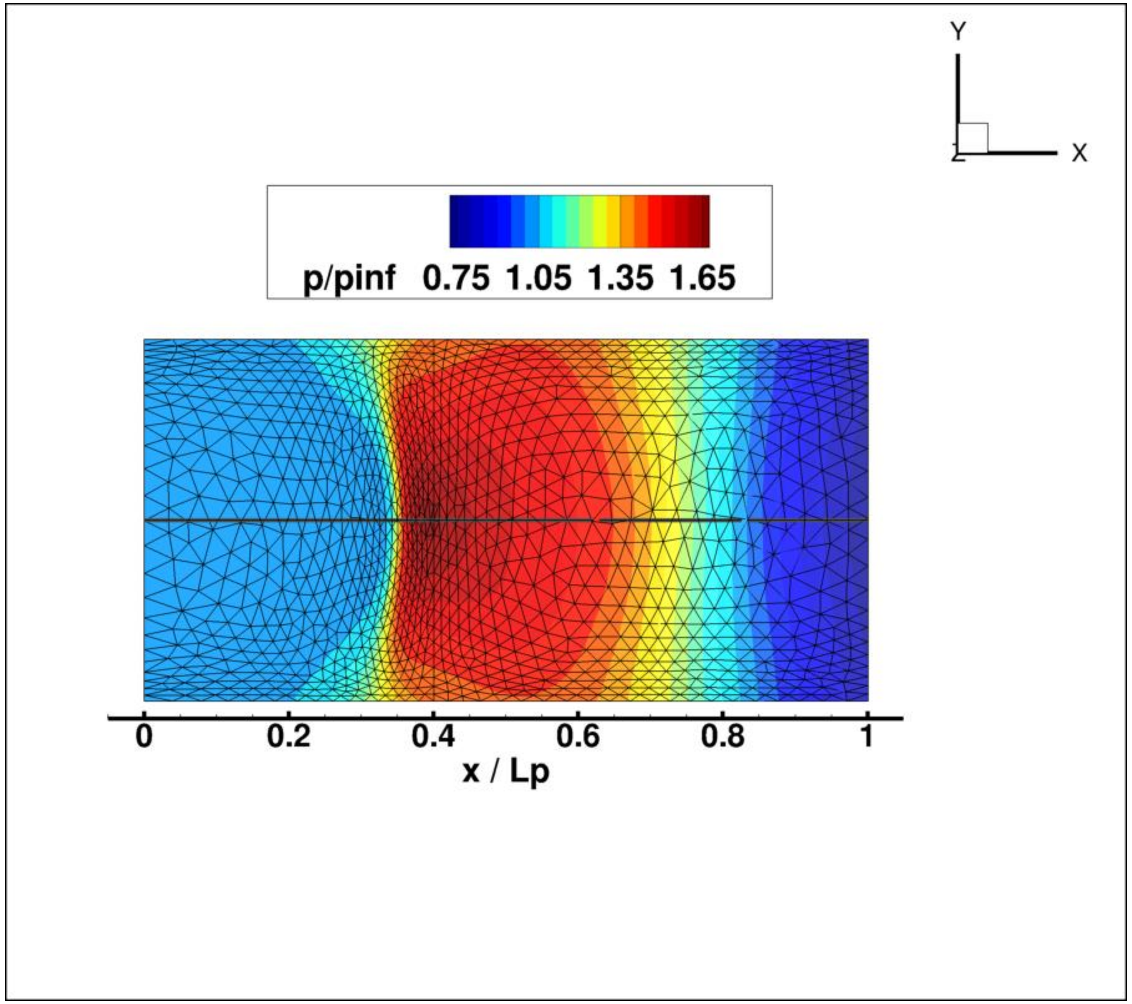




Test Case 3 Mesh Adaptation (Rigid)

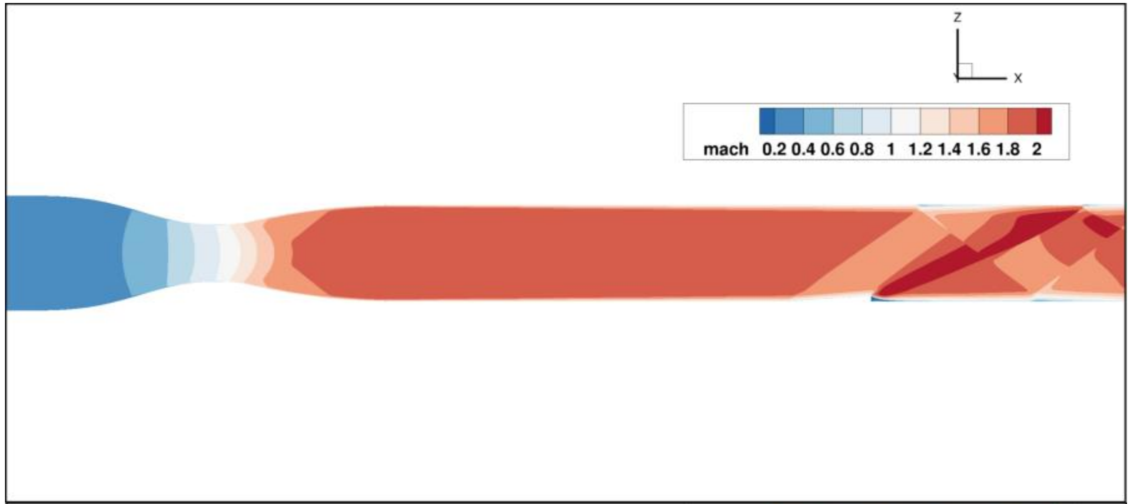
Mesh size: 2273977

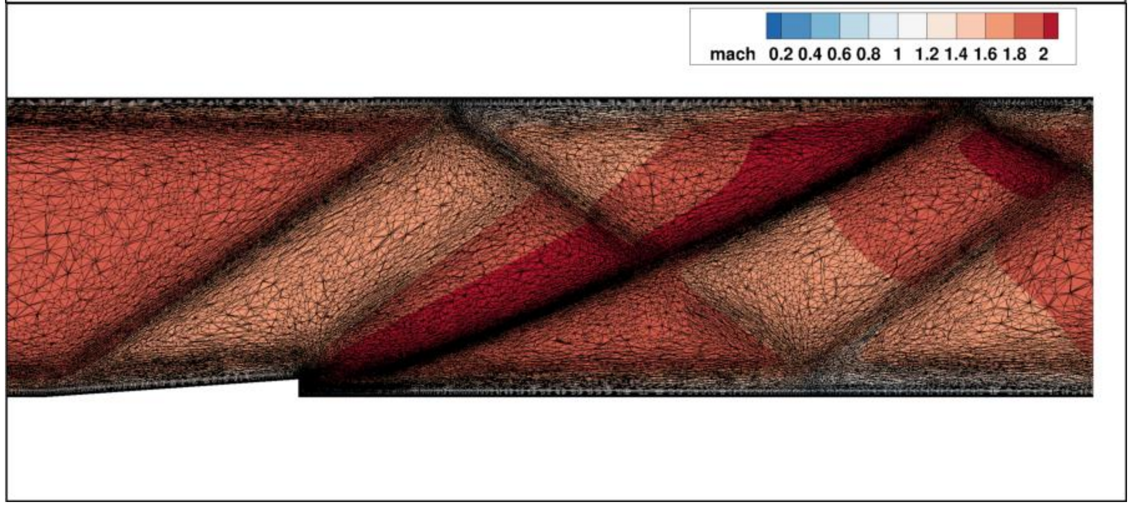


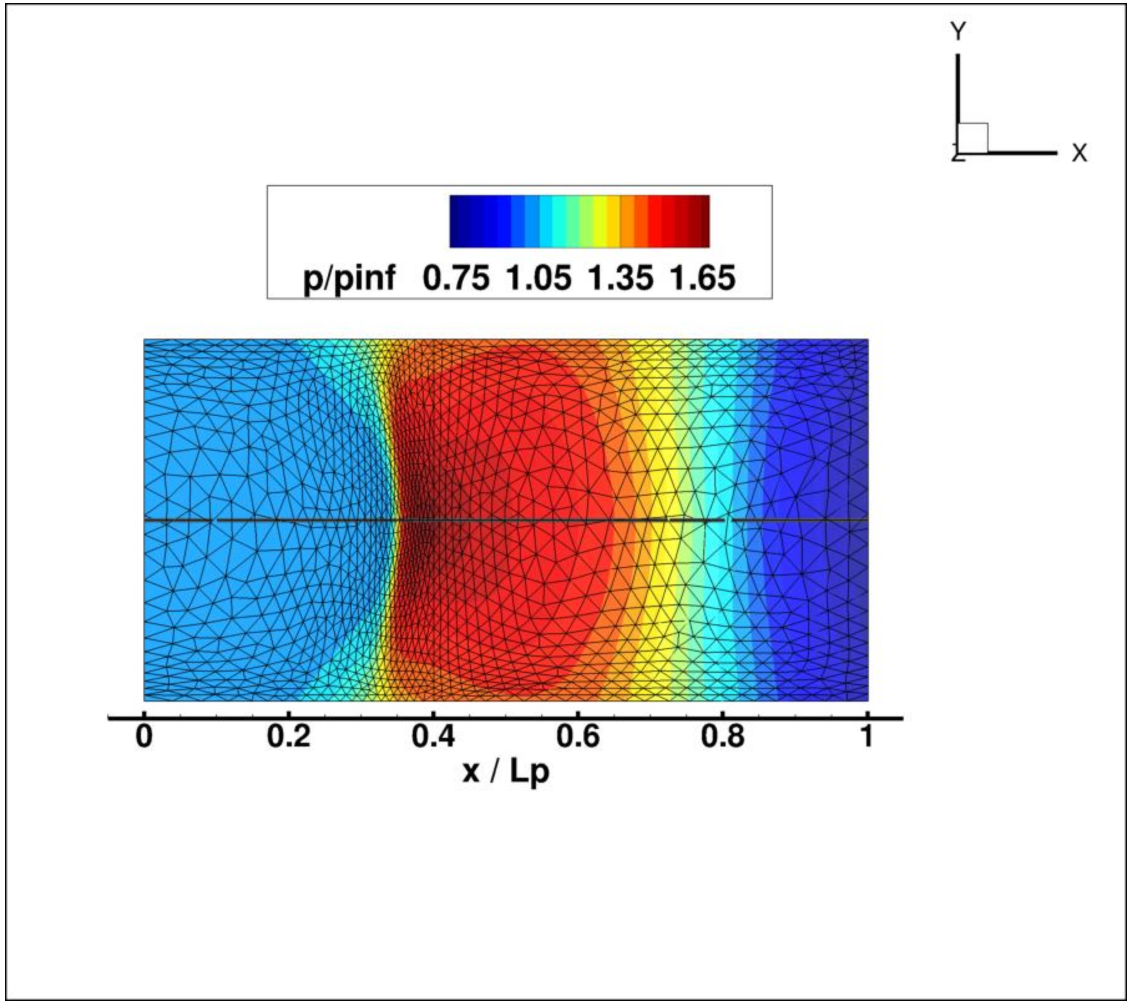


Test Case 3 Mesh Adaptation (Rigid)

Mesh size: 2707081 – used in aeroelastic analysis

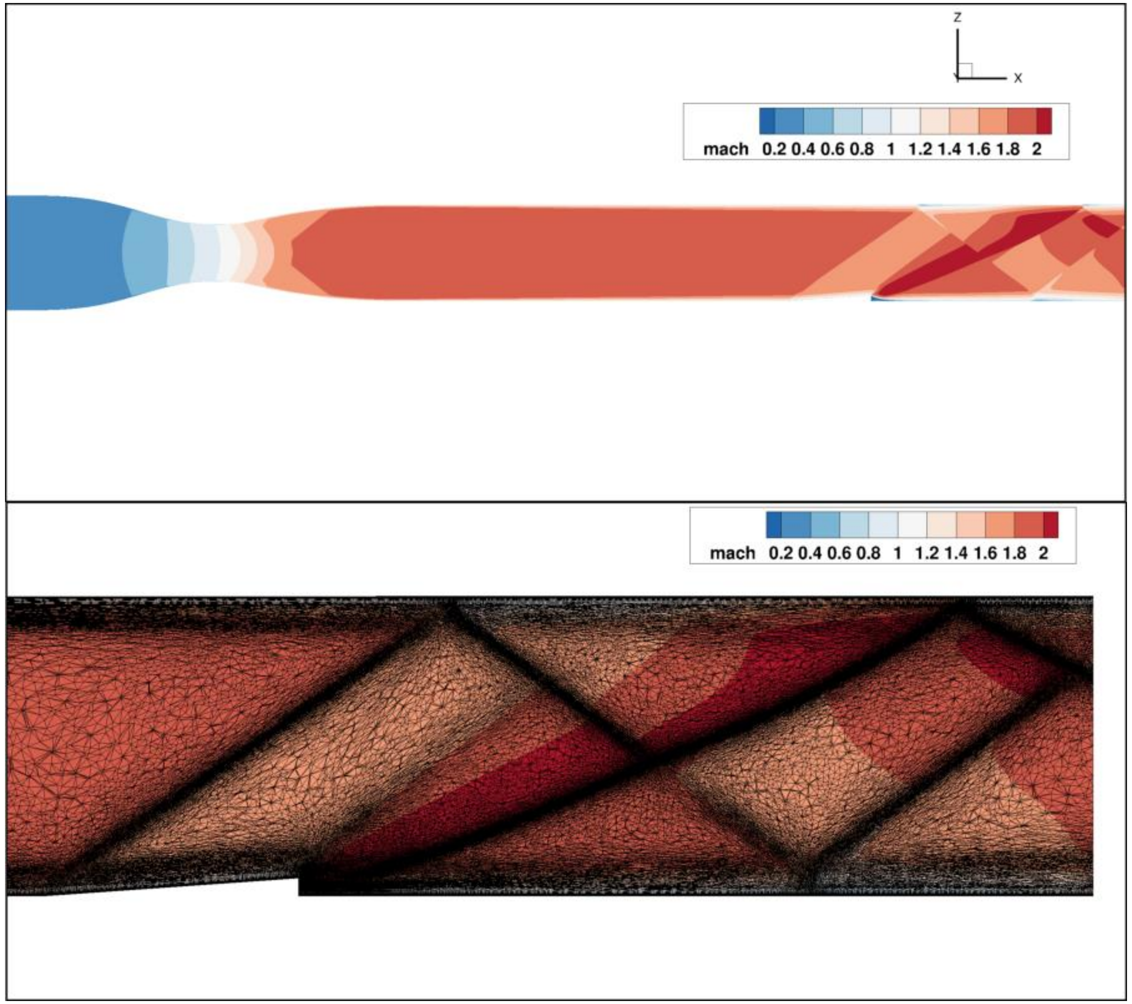


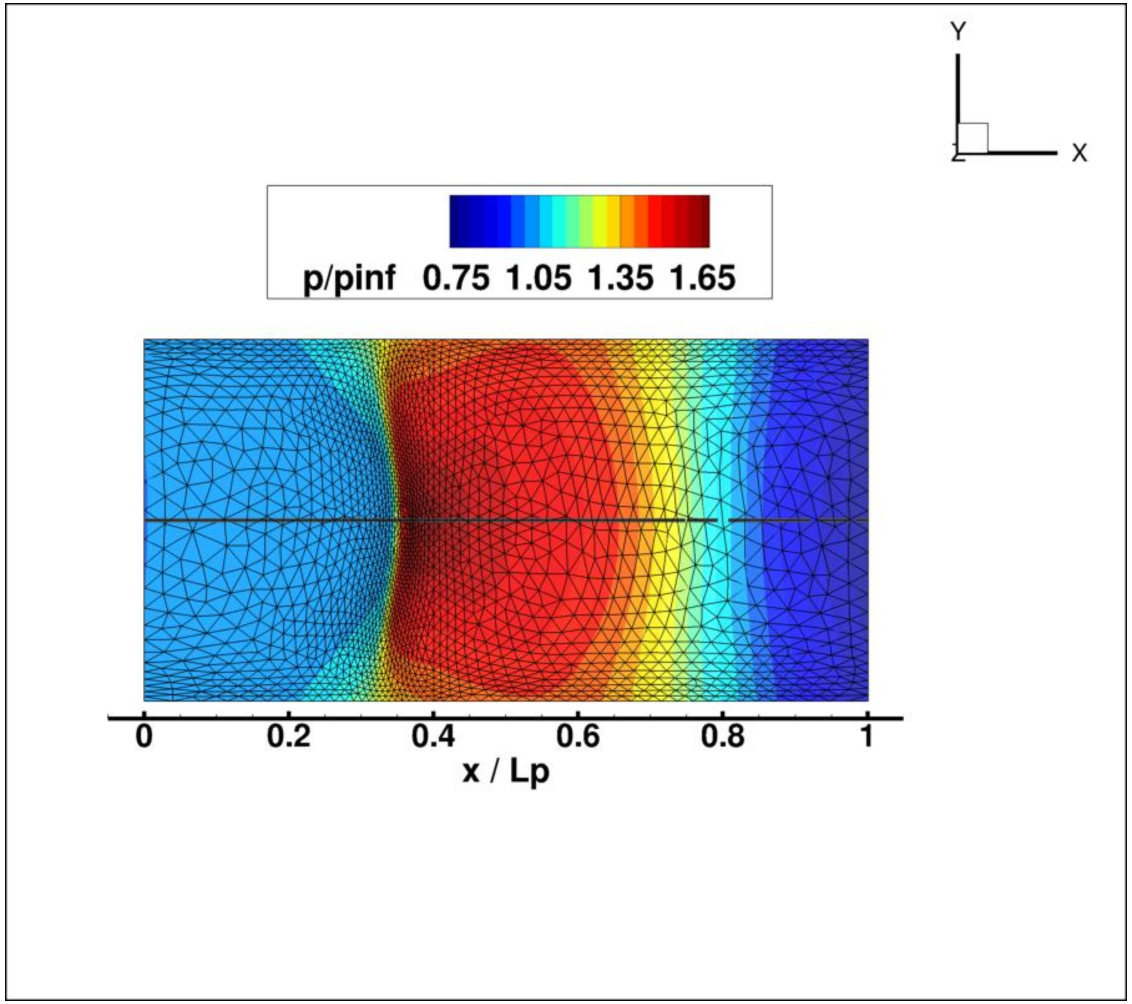




Test Case 3 Mesh Adaptation (Rigid)

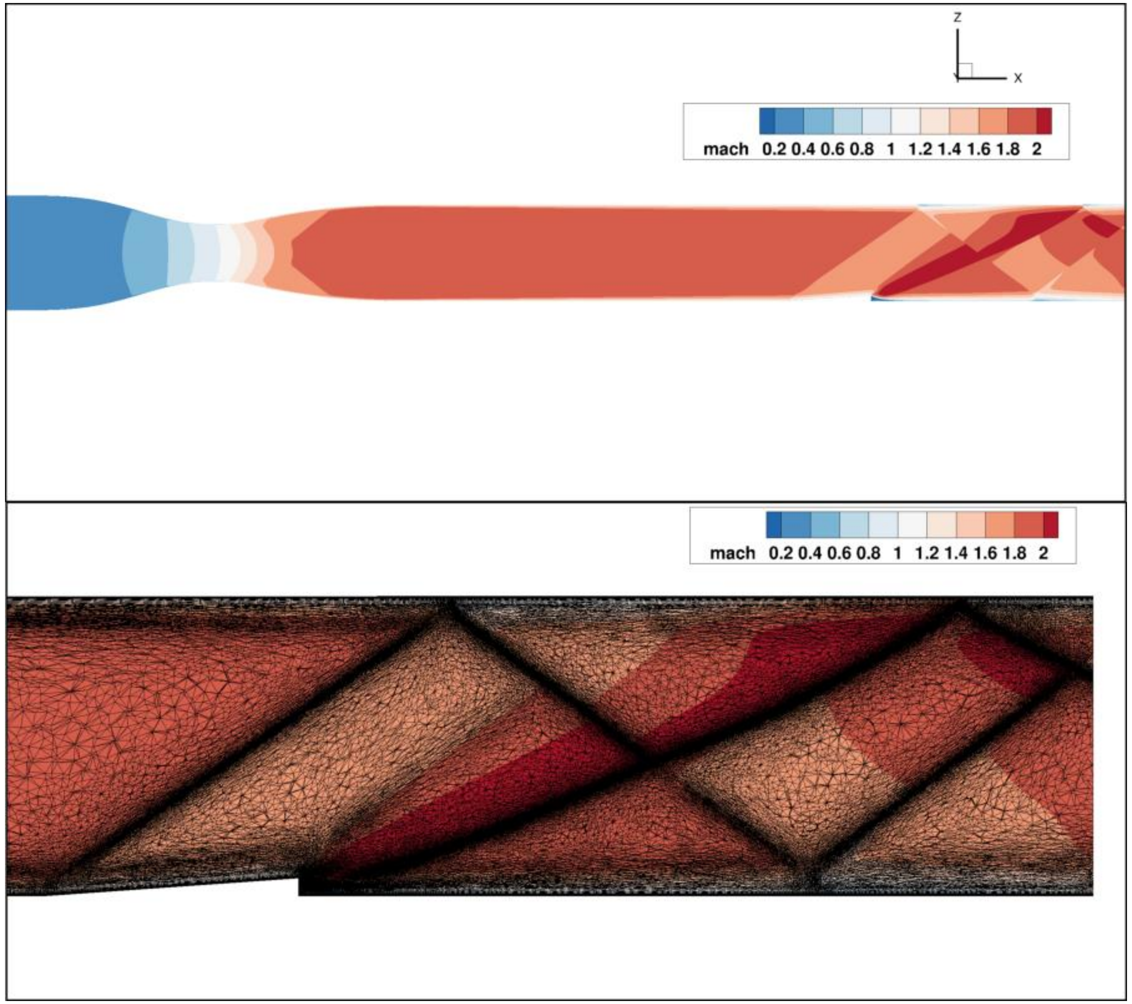
Mesh size: 4604601

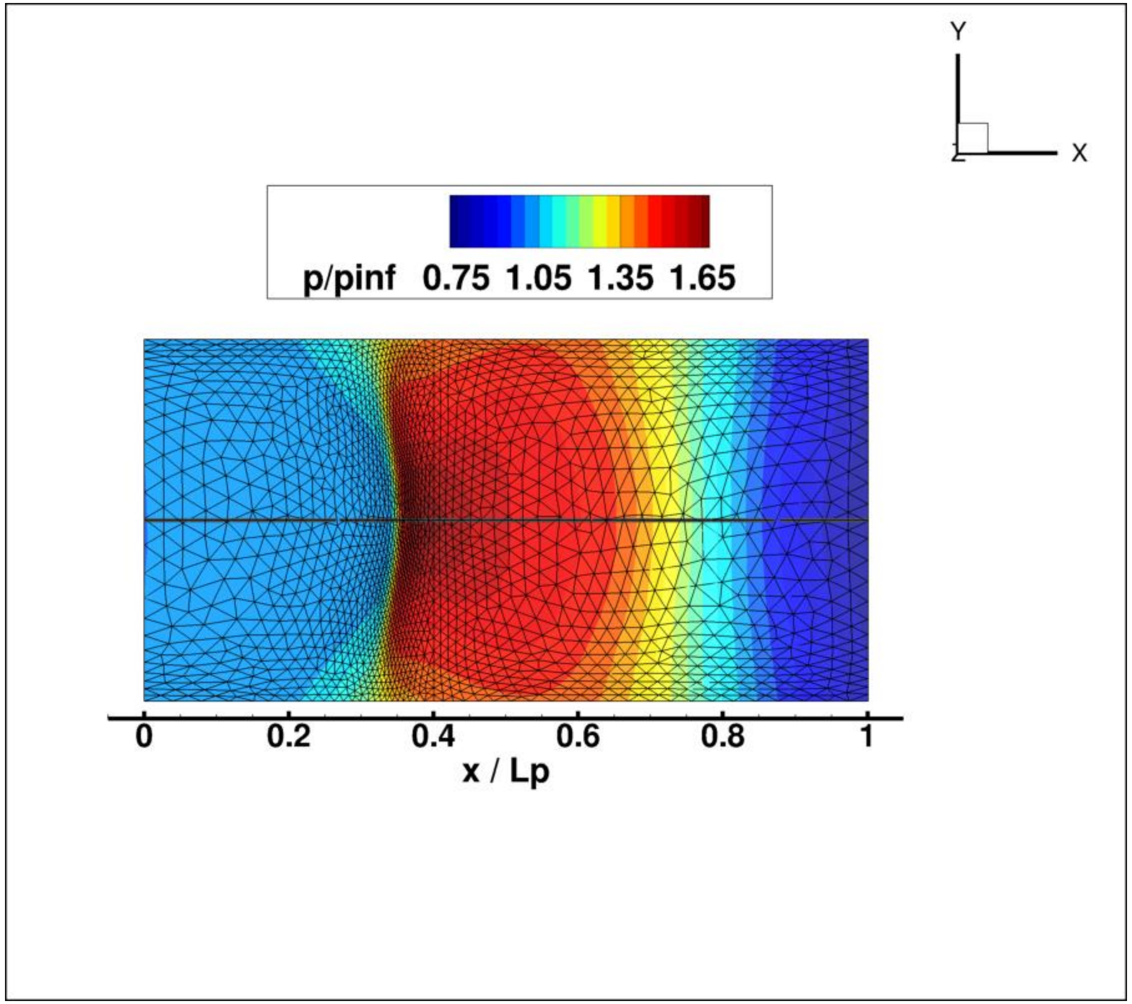




Test Case 3 Mesh Adaptation (Rigid)

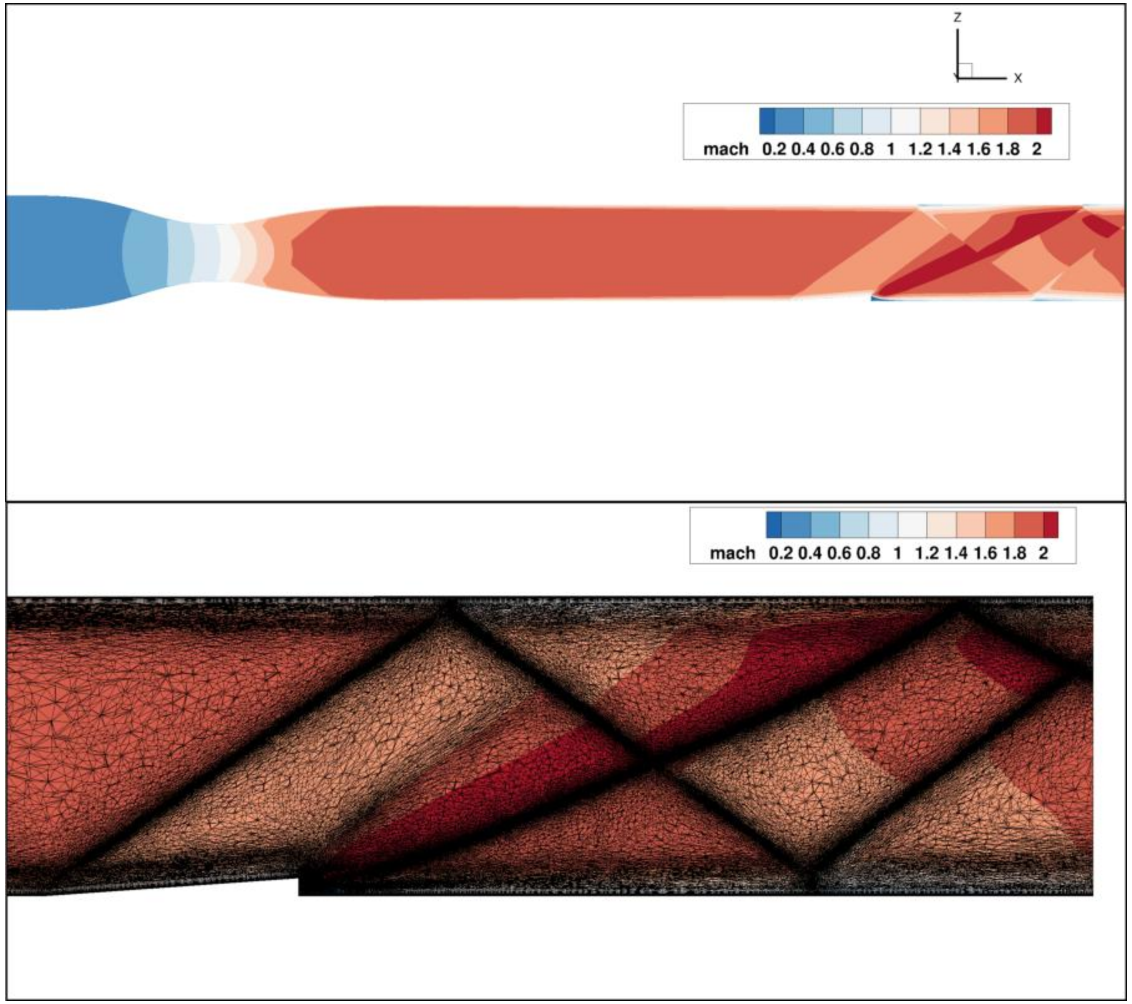
Mesh size: 4462465

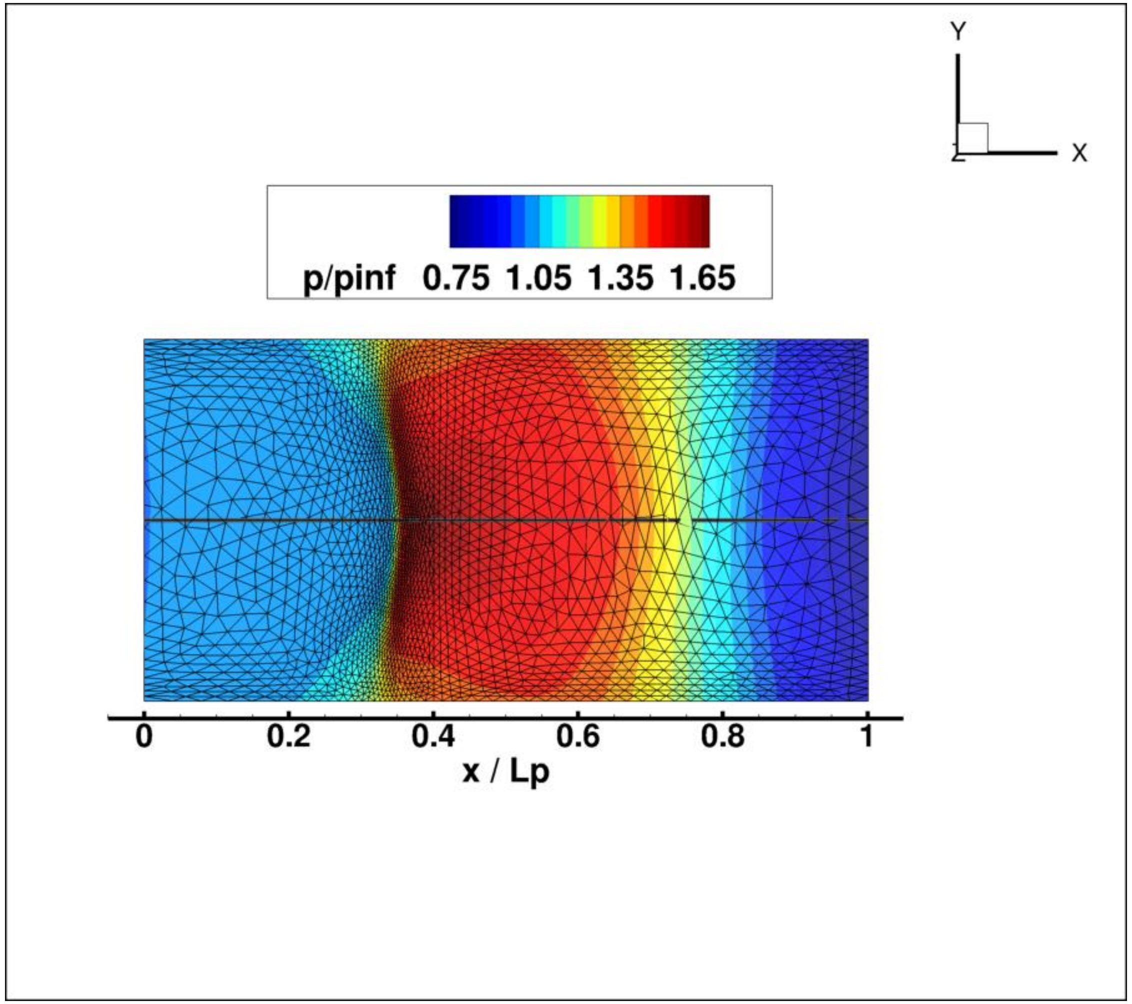




Test Case 3 Mesh Adaptation (Rigid)

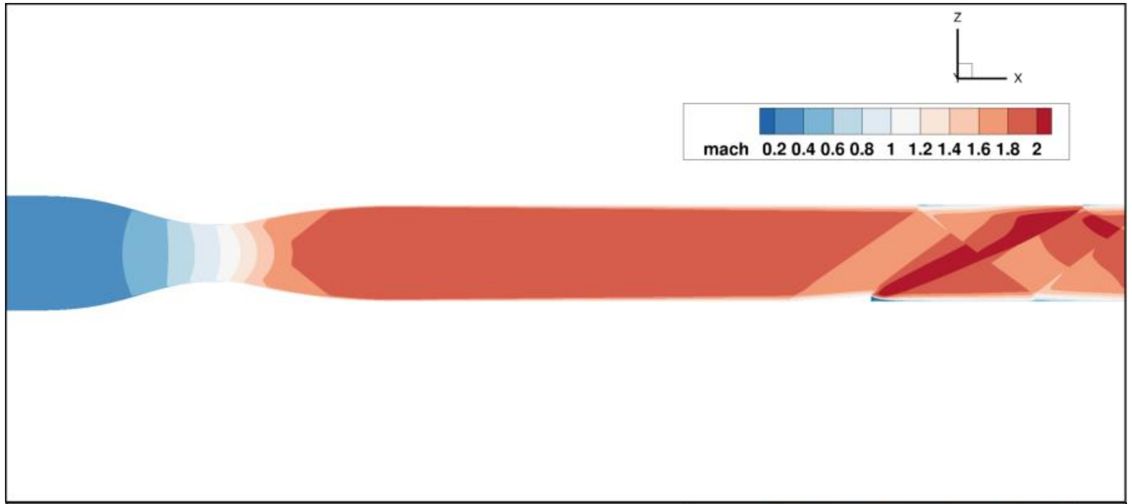
Mesh size: 7669585

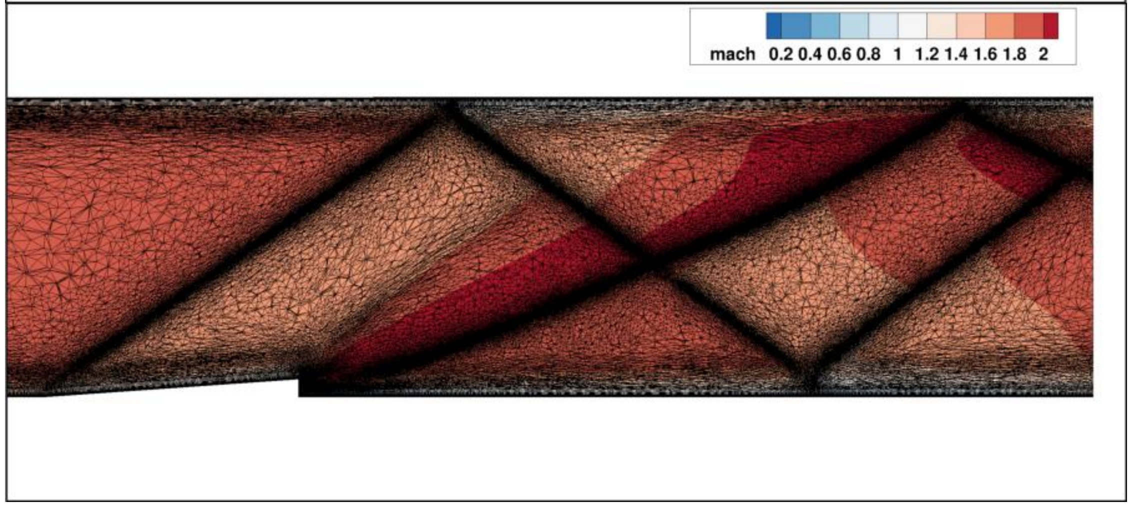


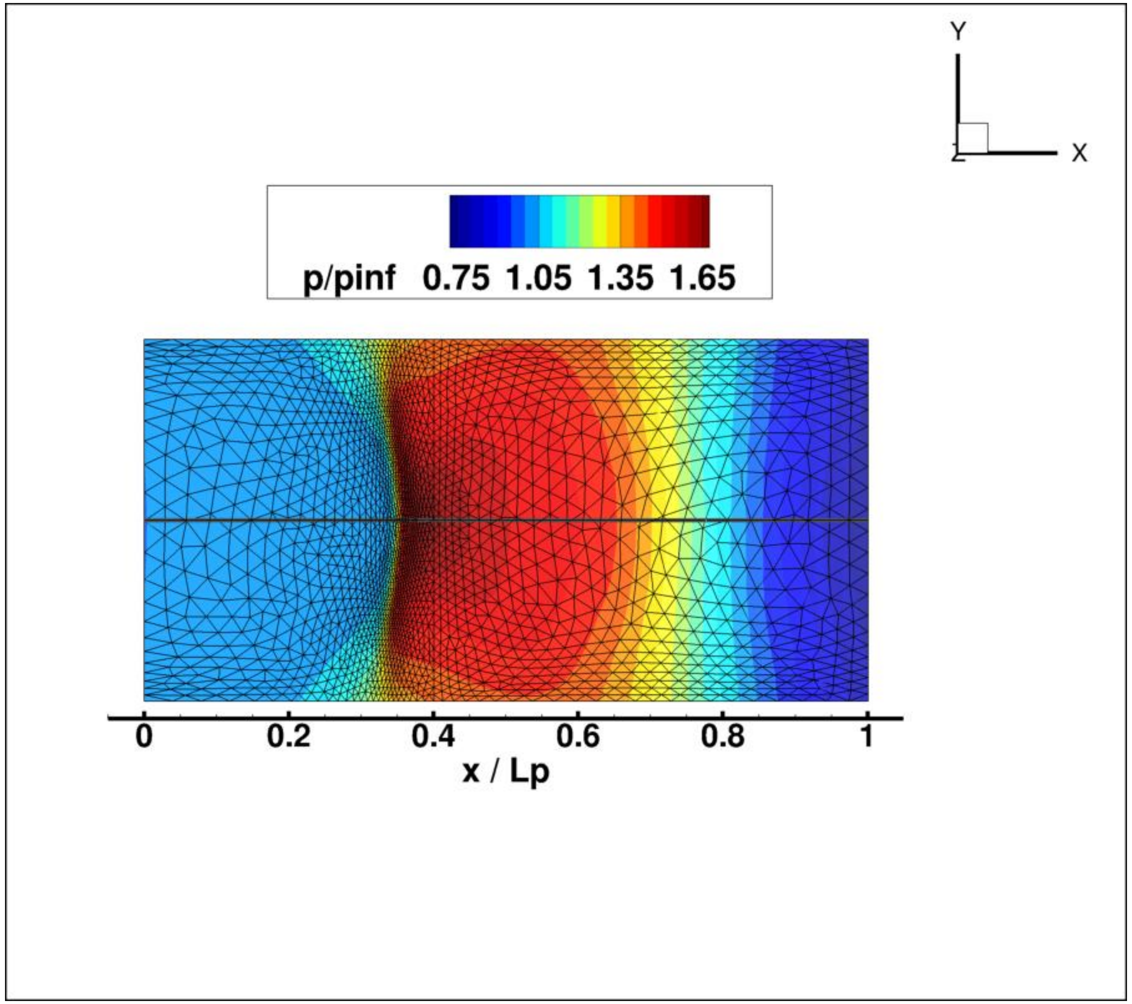


Test Case 3 Mesh Adaptation (Rigid)

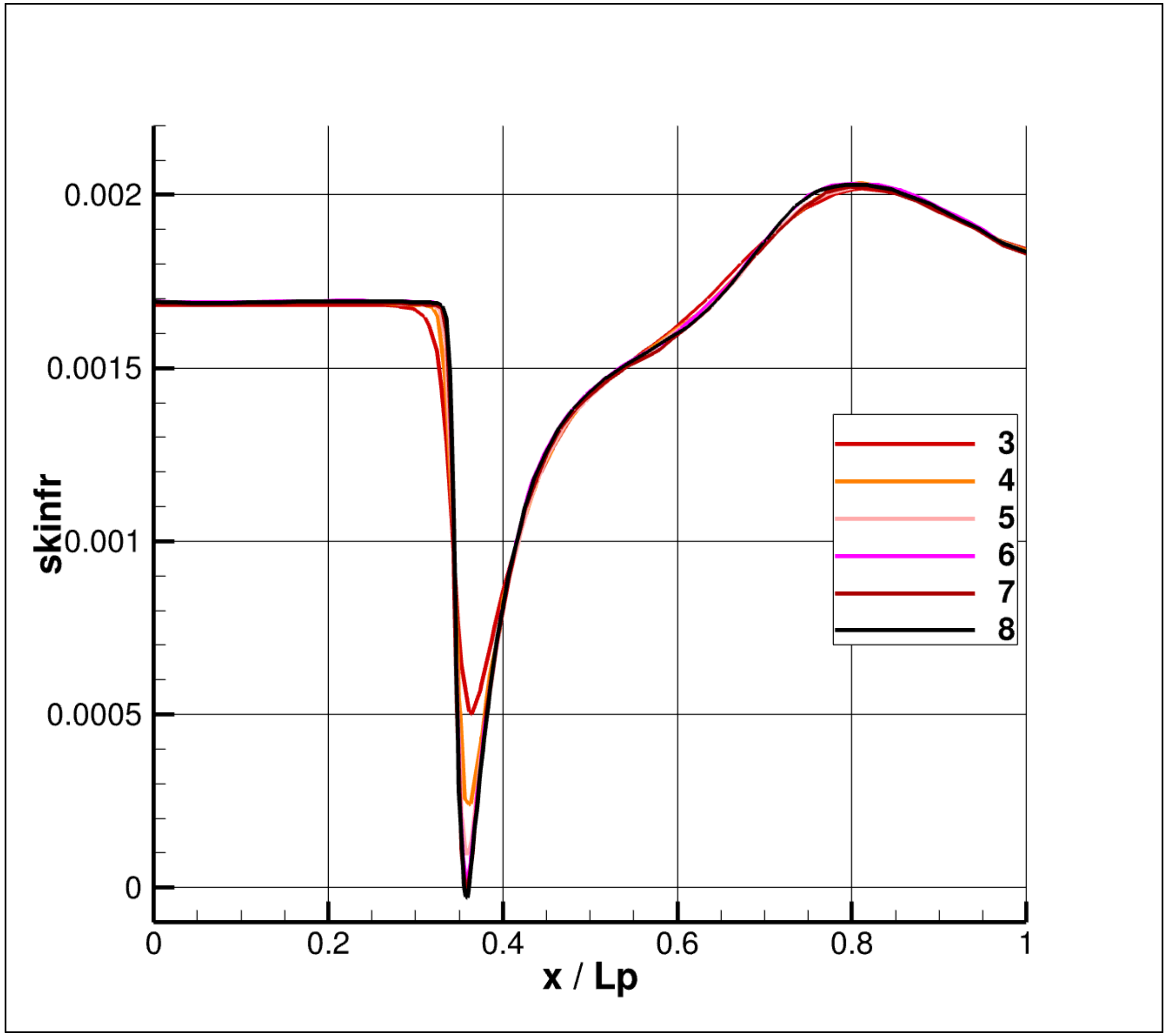
Mesh size: 7248795

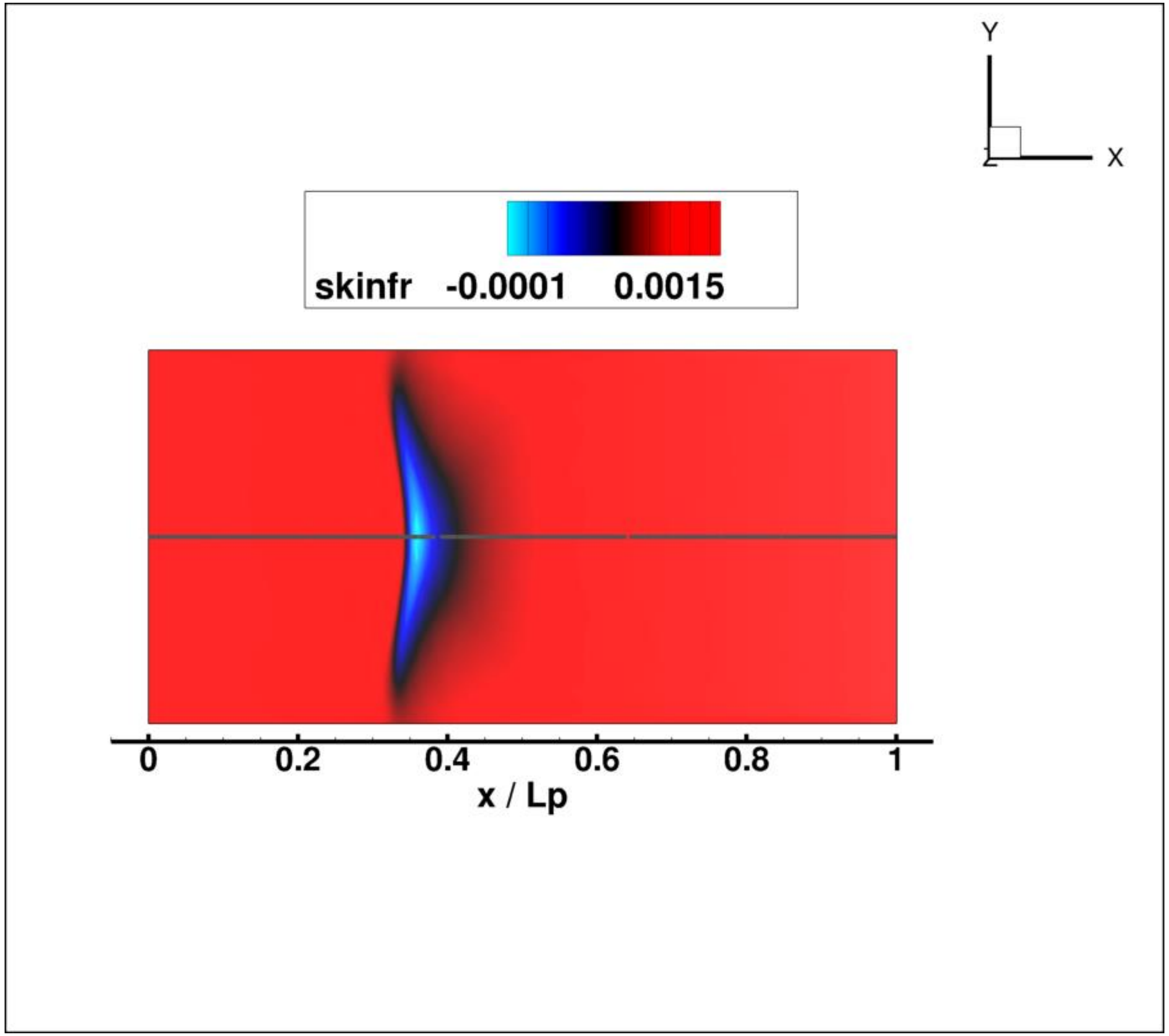






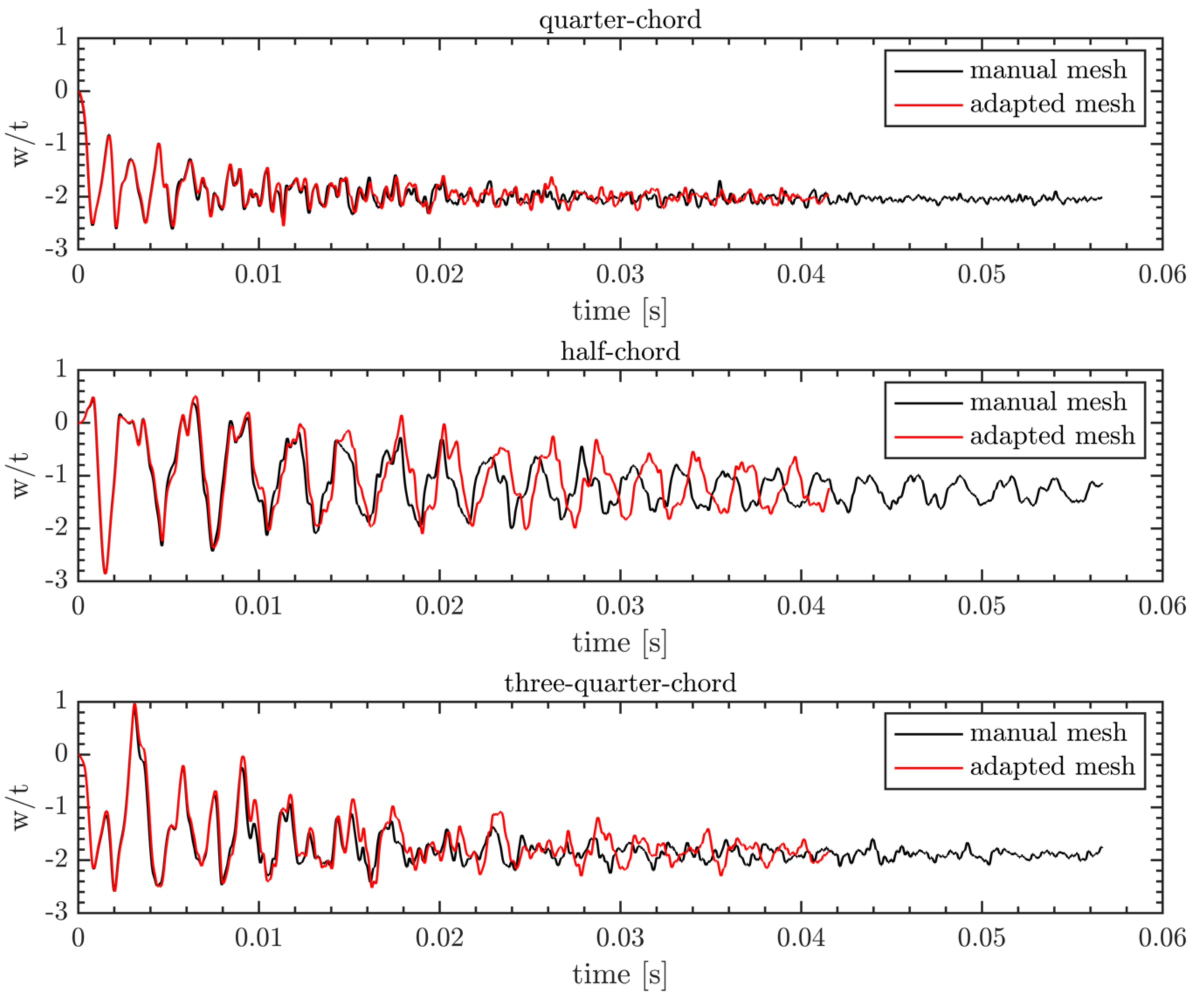
Adapted Mesh Skin Friction



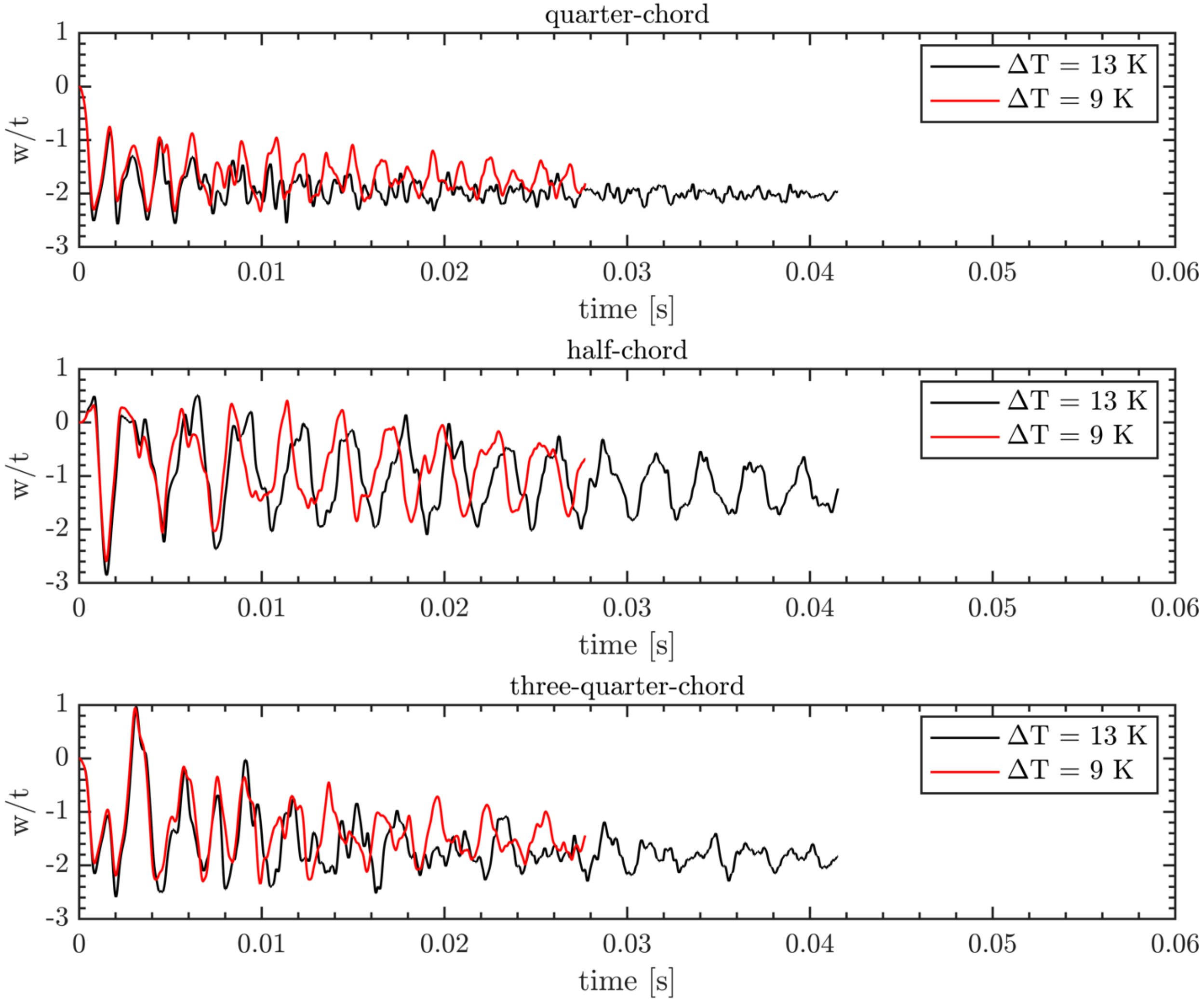


Aeroelastic Analysis of the Refined Mesh

- Use the mid-size 2.7M-node adapted mesh
- Compare with results from the manually-constructed mesh

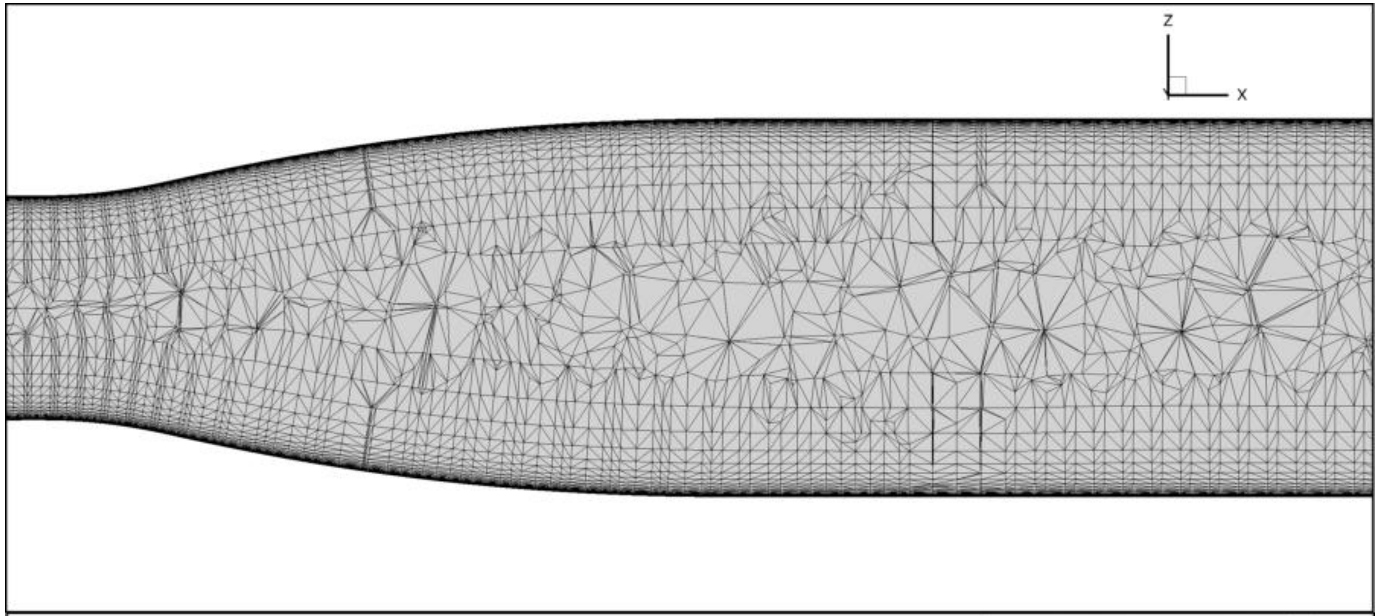


Refined Mesh at Lower Panel Temperatures



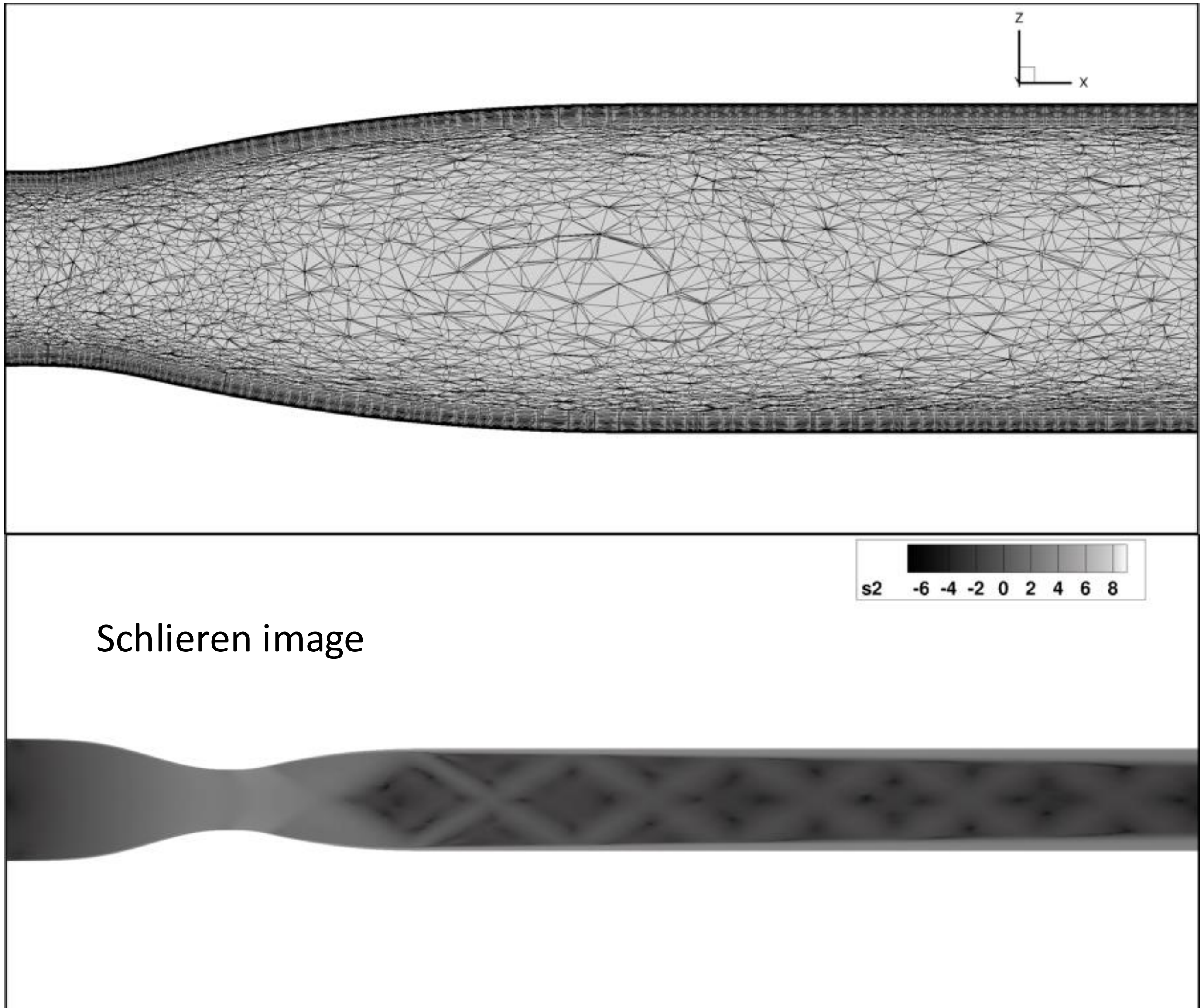
Mesh Adaptation w/o the Wedge

Mesh size: 406292



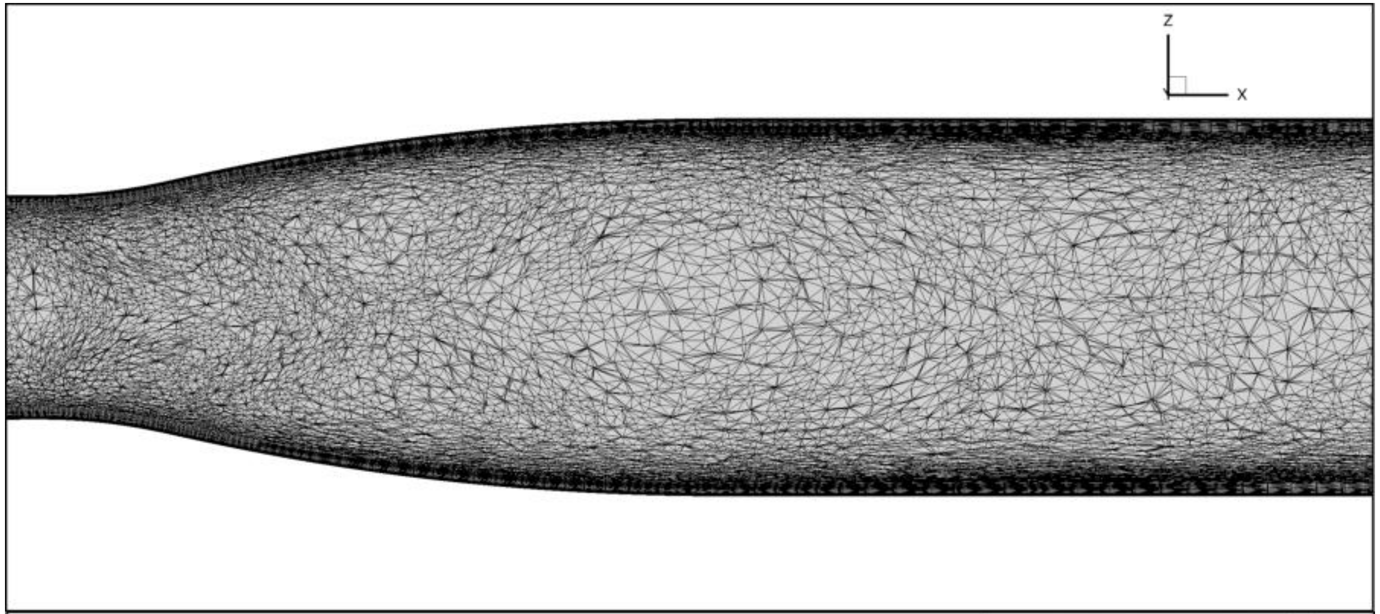
Mesh Adaptation w/o the Wedge

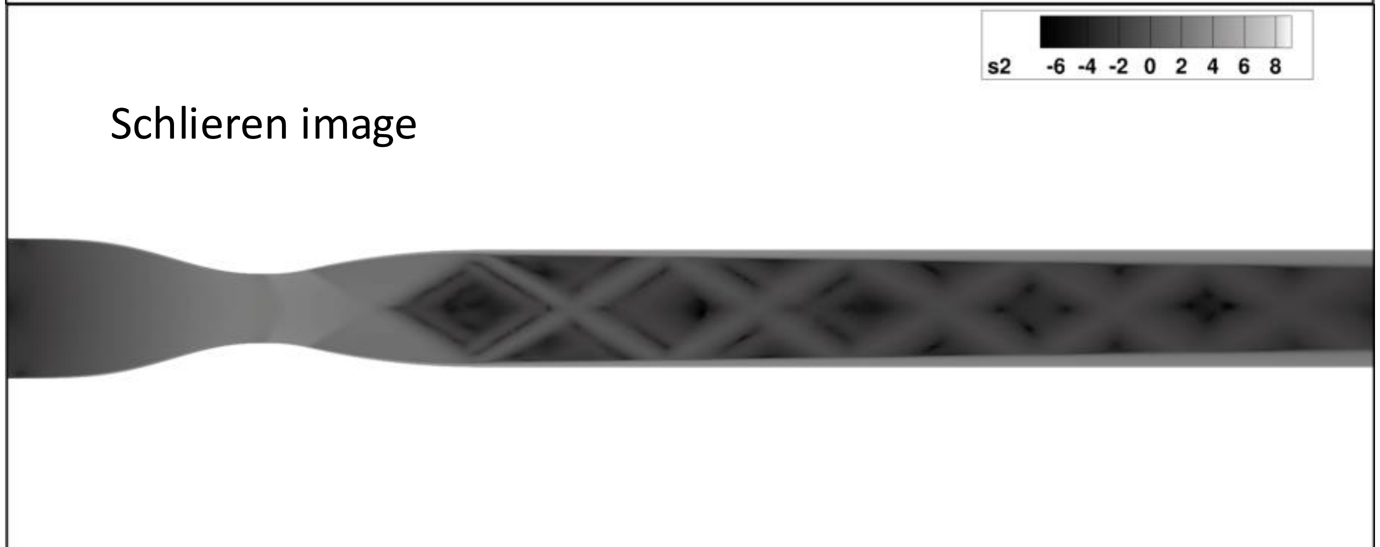
Mesh size: 1118478



Mesh Adaptation w/o the Wedge

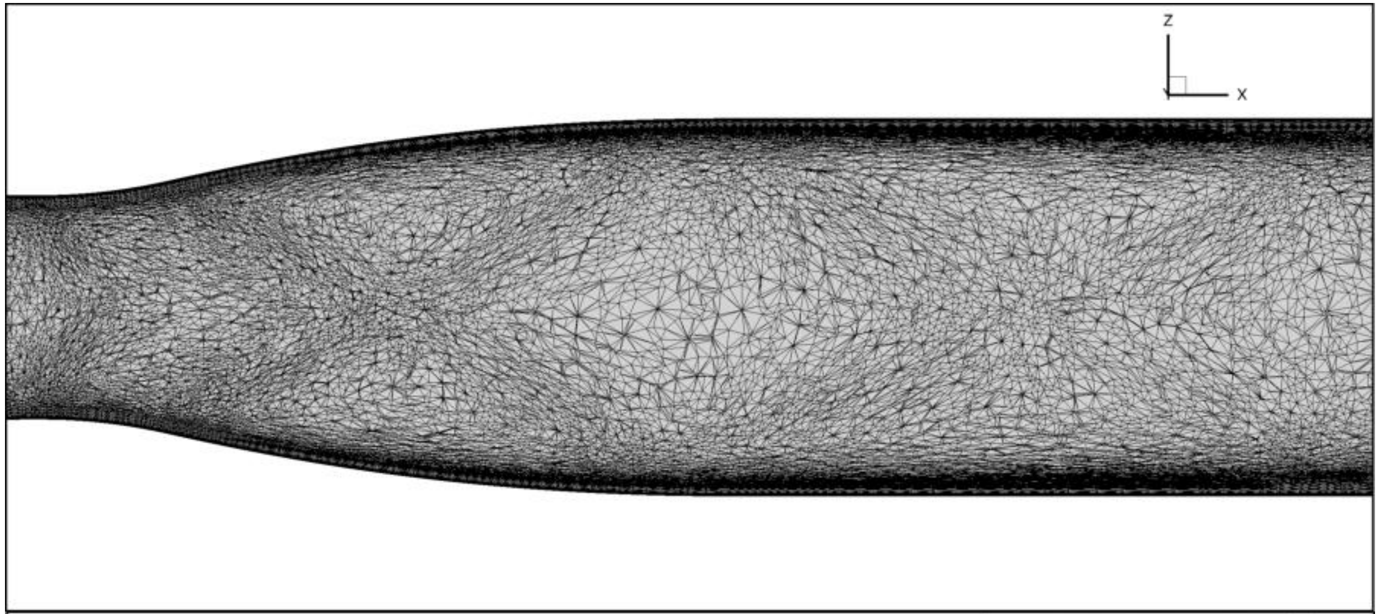
Mesh size: 1600833

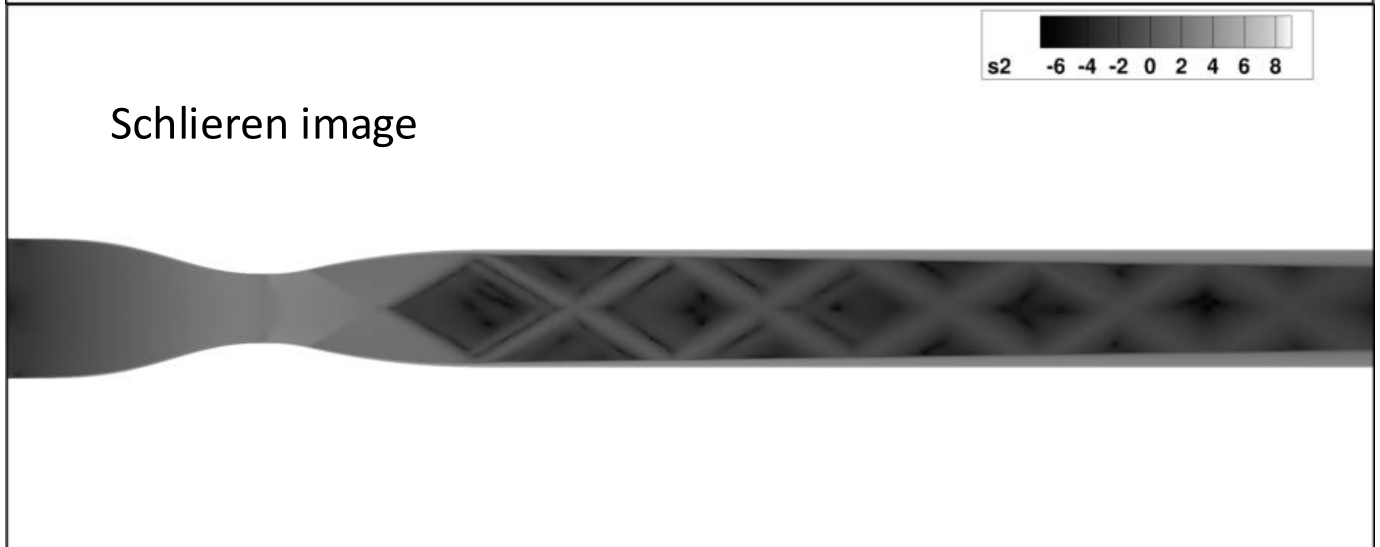




Mesh Adaptation w/o the Wedge

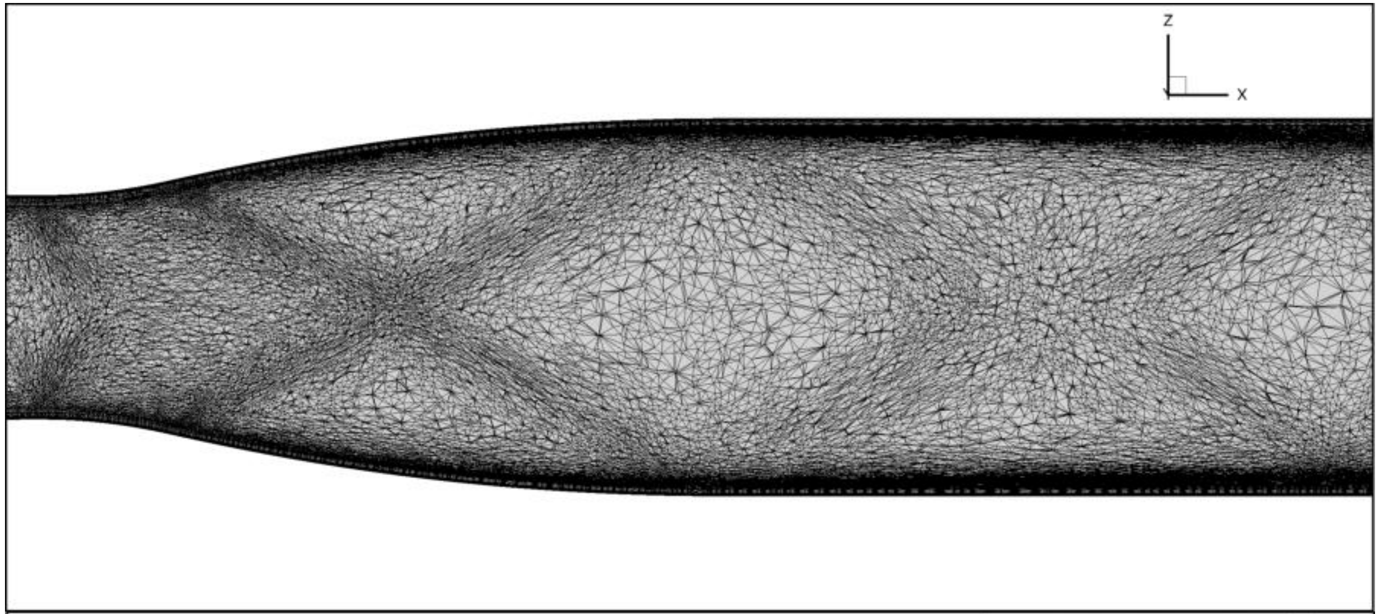
Mesh size: 1924280

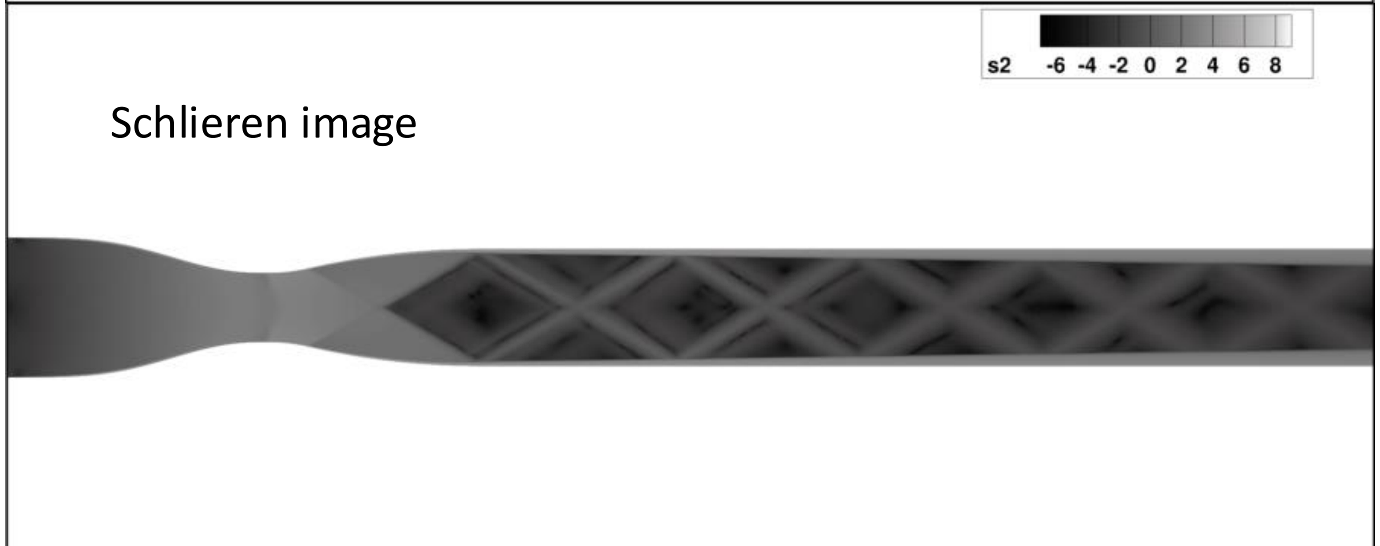




Mesh Adaptation w/o the Wedge

Mesh size: 2886763

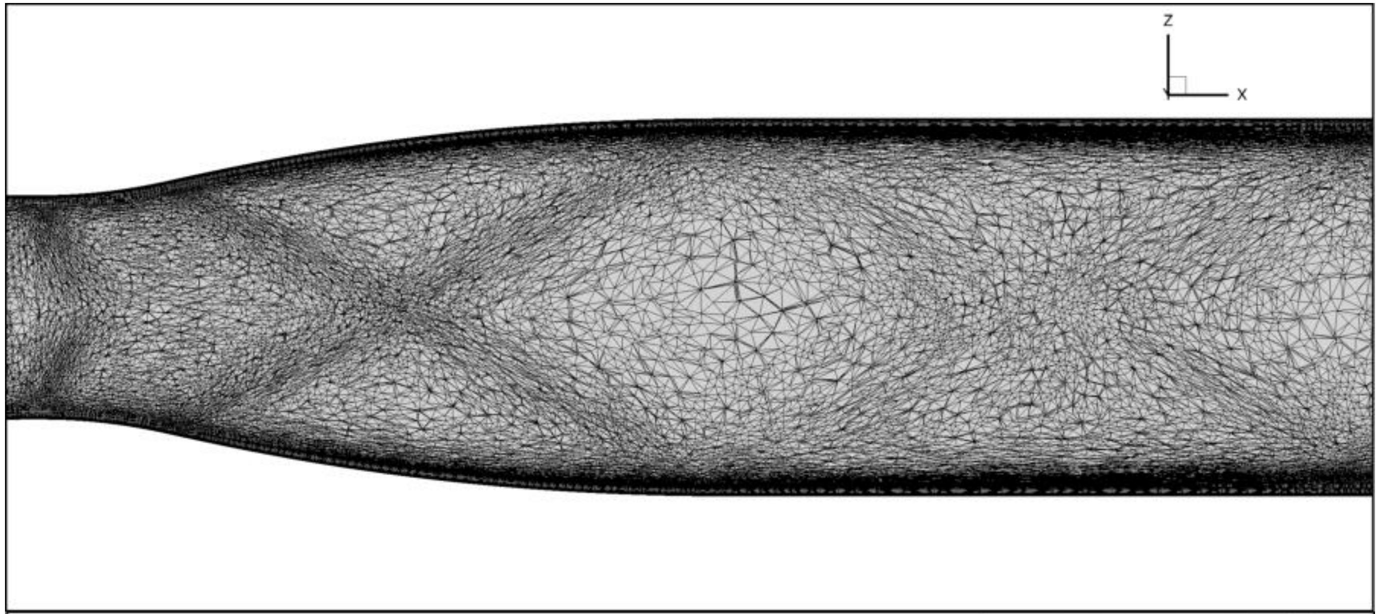


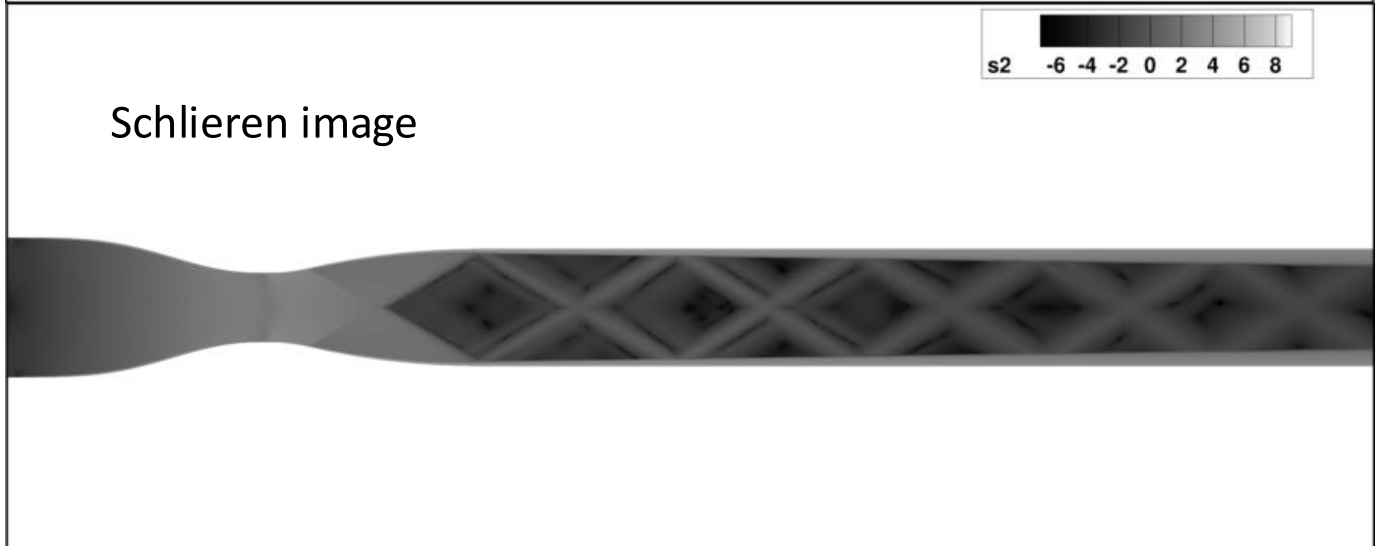


Schlieren image

Mesh Adaptation w/o the Wedge

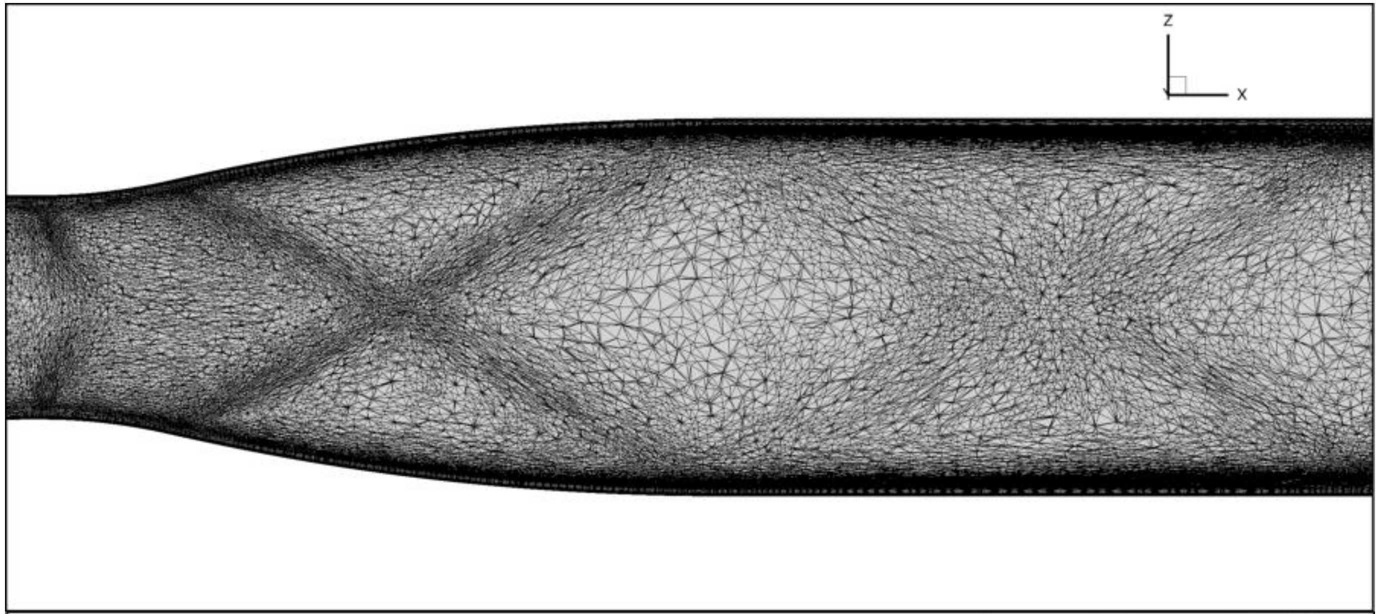
Mesh size: 2374397

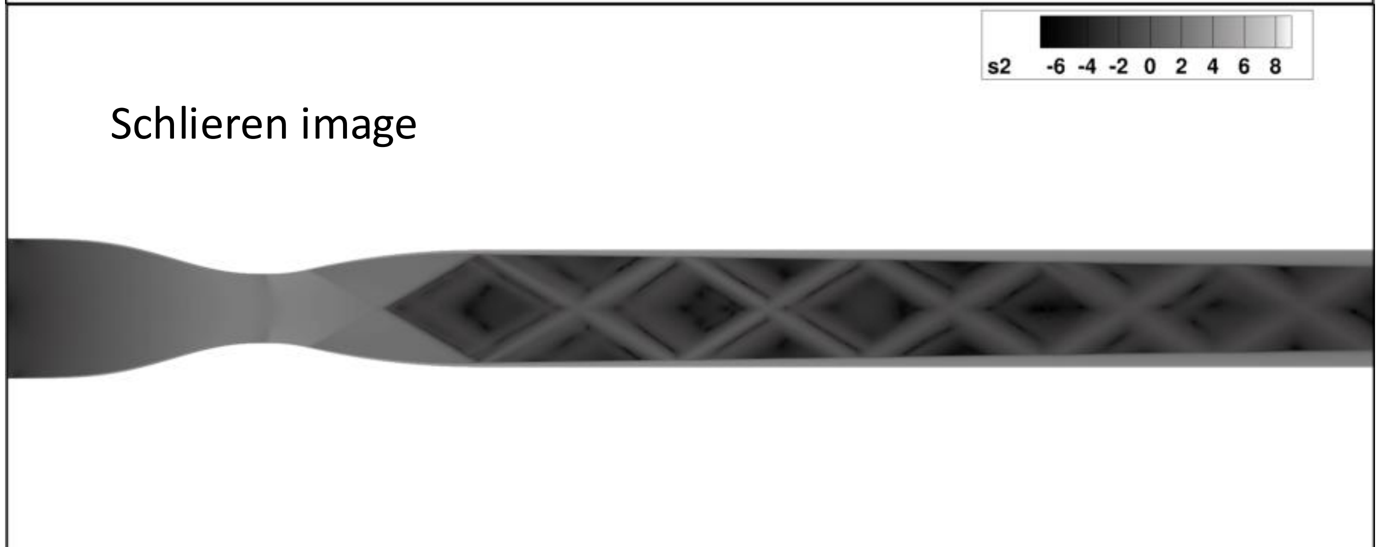




Mesh Adaptation w/o the Wedge

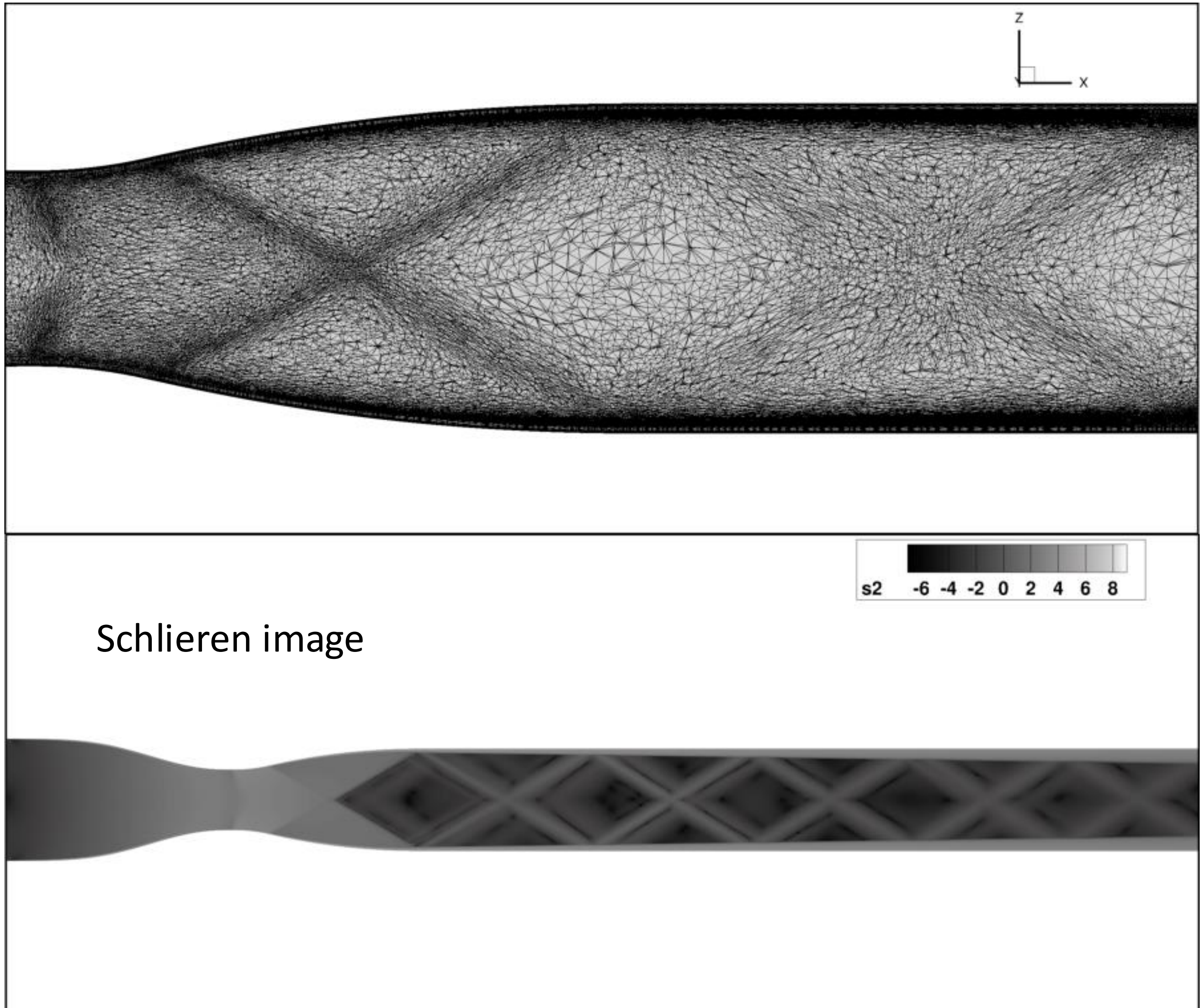
Mesh size: 3282571





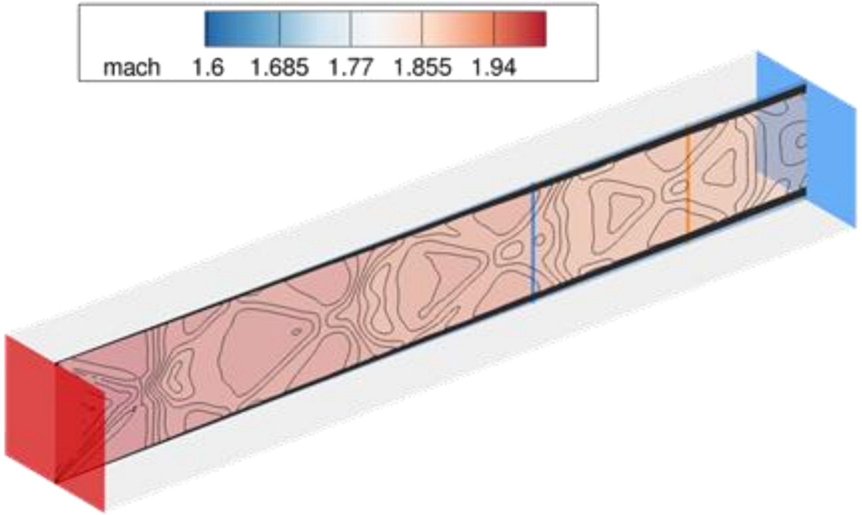
Mesh Adaptation w/o the Wedge

Mesh size: 3812357



Going Forward

- Modeling the nozzle seems to be having an effect on our aeroelastic results
  - Model the flow transition in the nozzle? Not sure we have the appetite for this
  - Ignore the nozzle altogether?
- In-plane stiffness of the panel supports:
  - Unclear what this stiffness should be
  - But in any case, there was no value of this stiffness that could get our model to flutter
- Panel temperature:
  - We are assuming that the panel temperature is uniform, but perhaps spatial variability is important?



Going Forward (2)

- RC19 prediction could benefit from some easily-digestible unit cases
  - With or without experimental data
- Pressure distribution on the rigid panel, w/ and w/o shock impingement
- Unsteady flow over the panel moving with some prescribed motion
- Thermal buckling of the panel under different pre-loads
  - w/ and w/o coupled static aeroelastic effects
- Vibration PSDs due to known, simple loading
  - Linear and nonlinear forcing levels

bret.k.stanford@nasa.gov