DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

Response Prediction of Compliant Structures in Hypersonic Flow

Jack J. McNamara

Students: Andrew Crowell (SMART), Brent Miller (SMART), Zach Riley, Rohit Deshmukh

CAEL

Computational AeroElasticity Laboratory

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Motivations & Objective

1. **Thin gauge hot structures** ***enable*** responsive hypersonic platforms

2. Response prediction of **thin gauge structures** in high speed flows requires ***coupled fluid-thermal-structural*** modeling & analysis.

3. Fluid-Thermal-Structural response is **trajectory dependent** (*& dependent on operational life w/ damage accumulation*).

4. Testing ***scaled multi-disciplinary*** models in wind tunnels is <u>impractical</u>.

5. ***Direct coupling*** of high fidelity numerical techniques for predicting vehicle response over a **trajectory and/or life** is <u>impractical.</u>

Require Improved Basic Understanding & Tractable Multi-Physics Approaches

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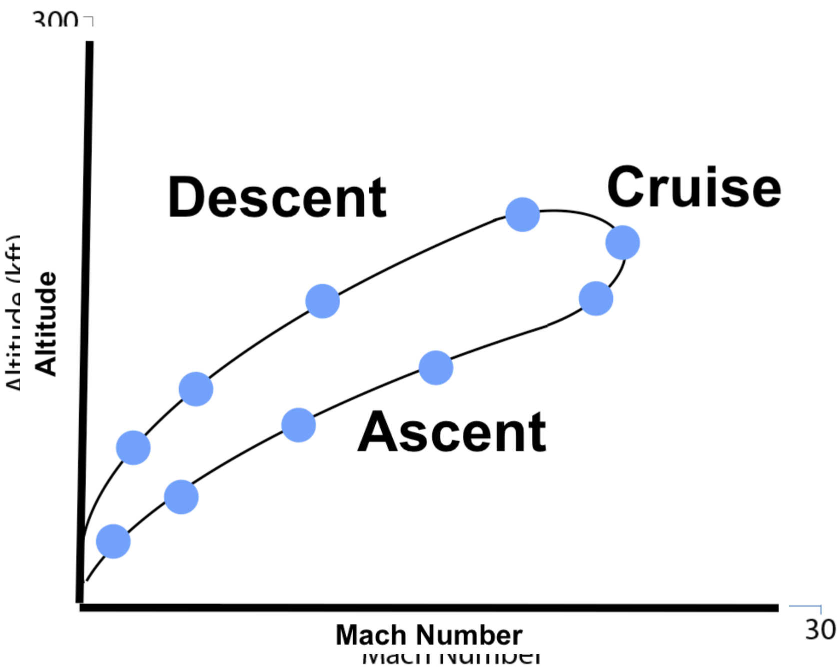
Standard Structural Design Practice

Standard Approach: **Develop a set of *uncoupled* load cases and spot check around operating conditions**



Aerodynamic heating and damage accumulation introduce large time-scale transients and path-dependence of the response

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Specific Research Themes

- **Thermo-Mechanical Response of Surface Panels to Shock Impingements** (Crowell and Miller)
  - **Time-marching and Coupling Reduction of Fluid-Thermal-Structural Interactions (FTSI)** (Brent Miller, SMART)
  - **Model Reduction of Aerothermodynamics** (Andrew Crowell, SMART)
- **The Impact of FTSI on Hypersonic Boundary Layer Transition** (Zach Riley, NDSEG starting Sept 2012)
- **Consideration of Turbulent Boundary Layer Loading in Structural Response Prediction** (Rohit Deshmukh)

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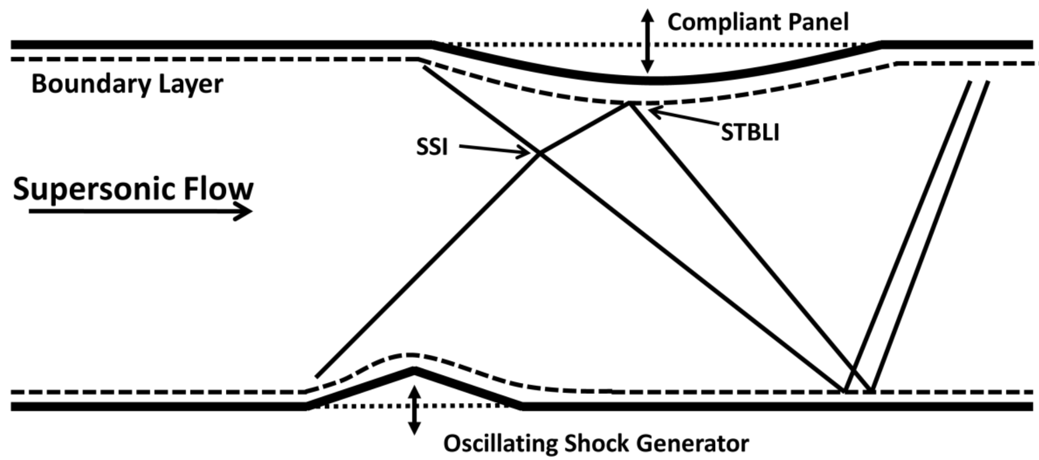
Shock Impingement on a Compliant Panel

Freestream Properties

Mach Number	3.0
Static Pressure	2970 Pa
Temperature	220 K
Density	0.04704 kg/m^2
Reynolds Number	2.914×10^4 m^{-1}



Oscillating Shock Generator

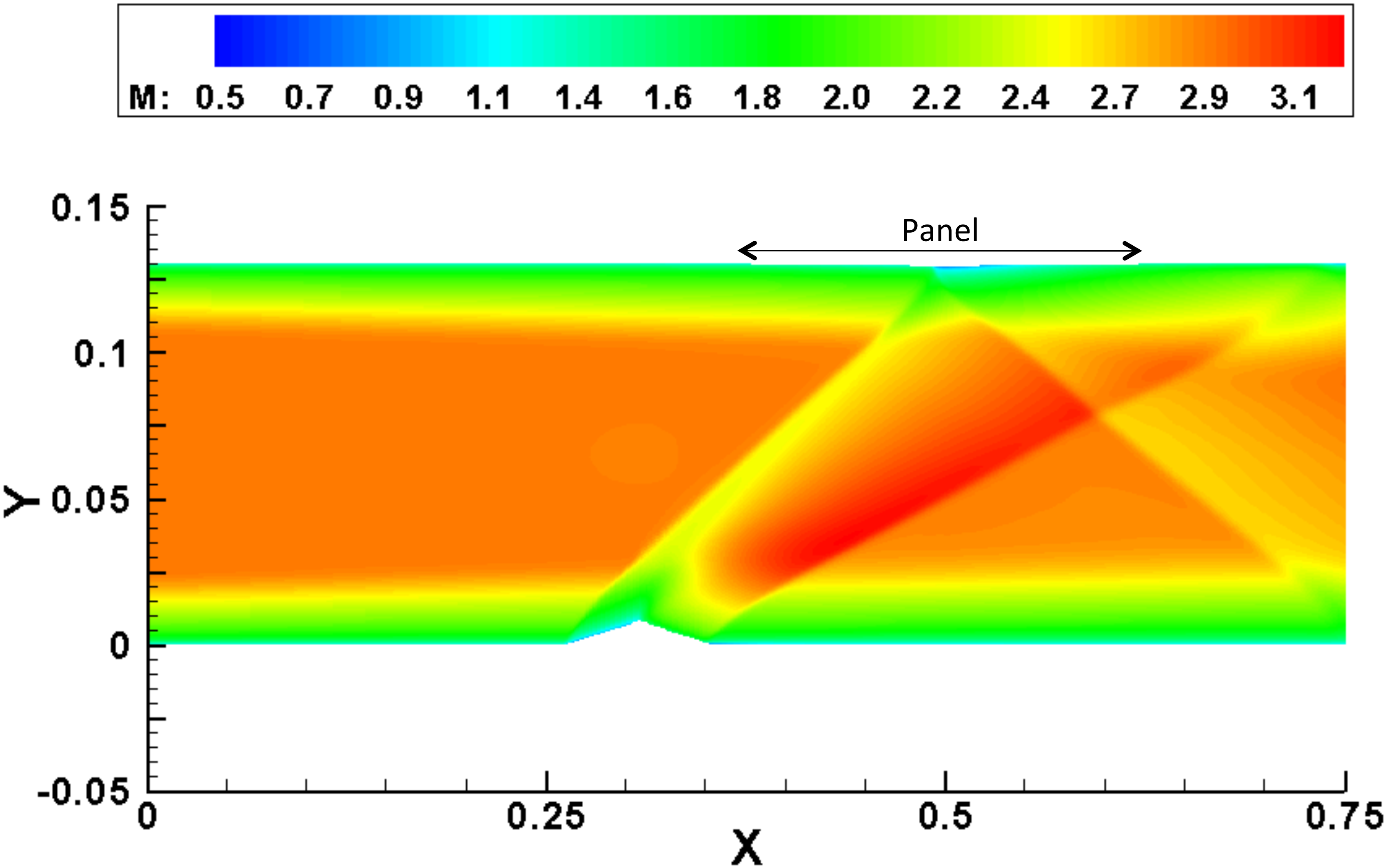
Frequency	10 Hz
Wedge angle range	7°-13°

Panel Properties

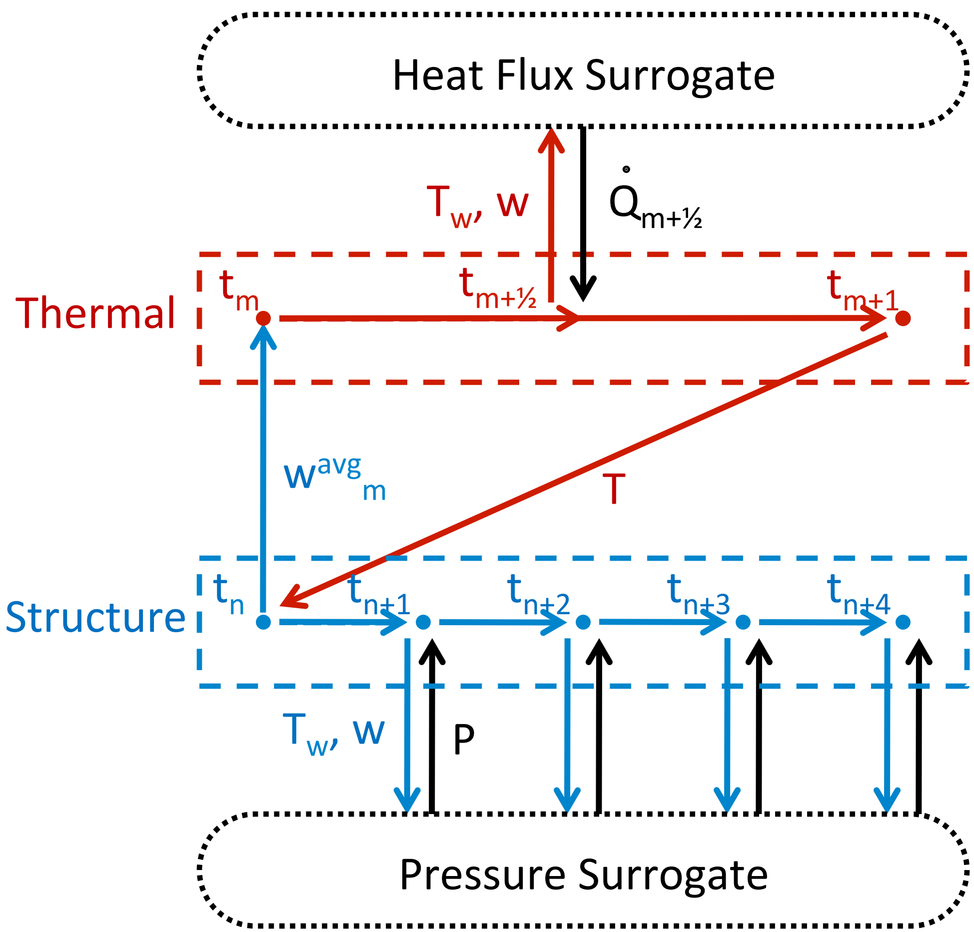
Material	Steel 4130
Length	25 cm
Thickness	0.7 mm
Initial Temperature	220 K

Miller, Crowell, McNamara, “Modeling and Analysis of Shock Impingements on Thermo-Mechanically Compliant Surface Panels,” AIAA-2012-1548, 2012.

Shock Impingement on a Compliant Panel



Fluid-Thermal-Structural Solution Scheme



Aerothermodynamic Surrogate

- NASA Langley CFL3D Flow Solver
- Quasi-static flow assumption
- < 6% error w/ unsteady comp. of temp response & aero forces

Thermal Solver

- 2D Finite Element Model
- 2nd order accurate Crank Nicolson time marching scheme

Structural Solver

- von Kàrmàn panel in cylindrical bending (nonlinear 1D panel model)
- Galerkin discretization w/ 15 modes
- 2^{nd} order accurate Newmark-β time marching scheme

All interpolations and extrapolations are at least second order accurate

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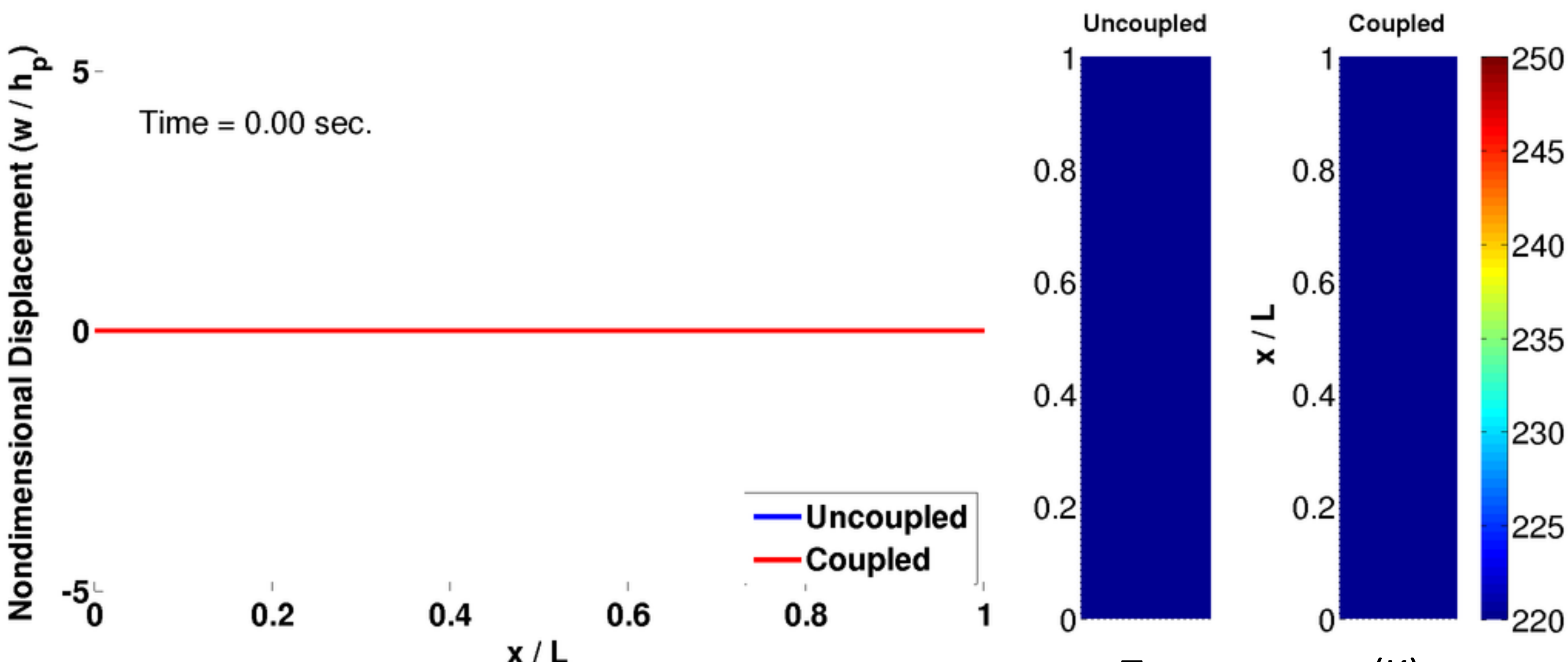
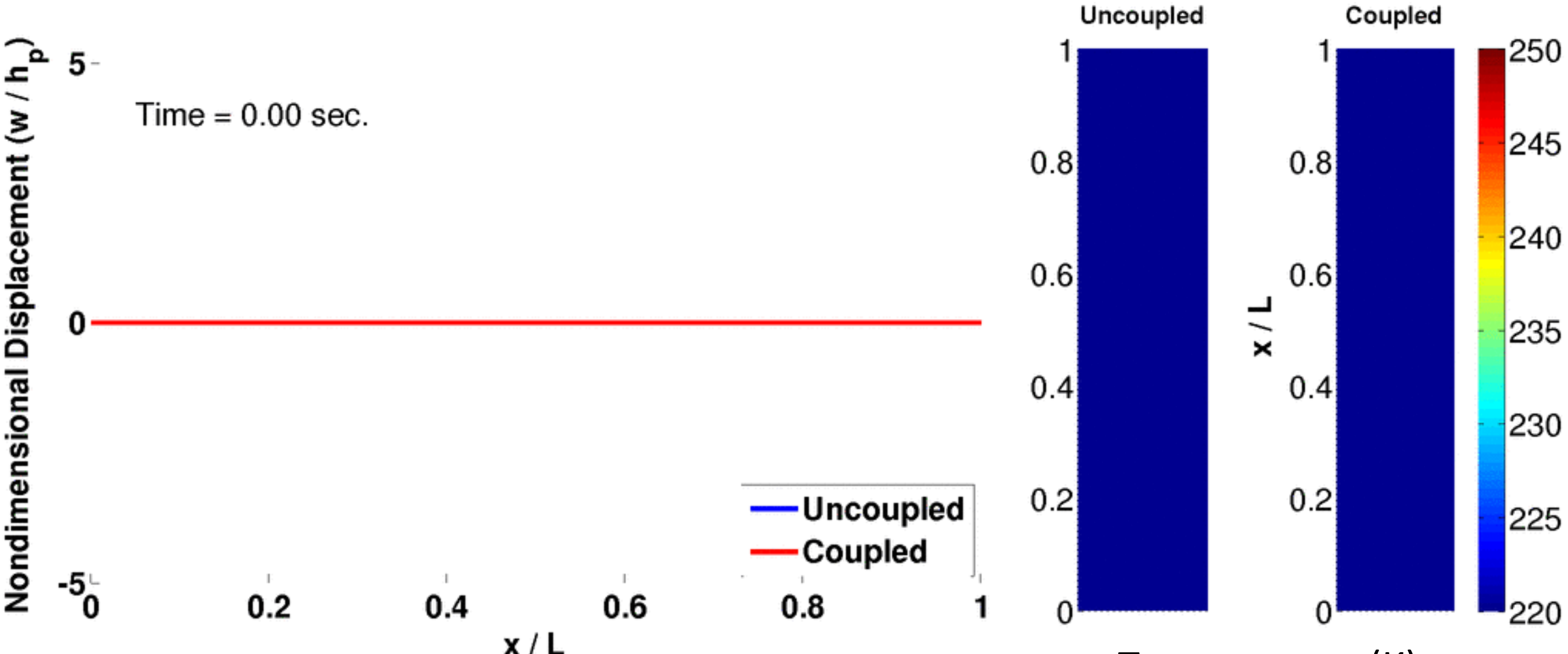
Thermo-Mechanical Response



Temperature (K)

Thermo-Mechanical Response



Temperature (K)

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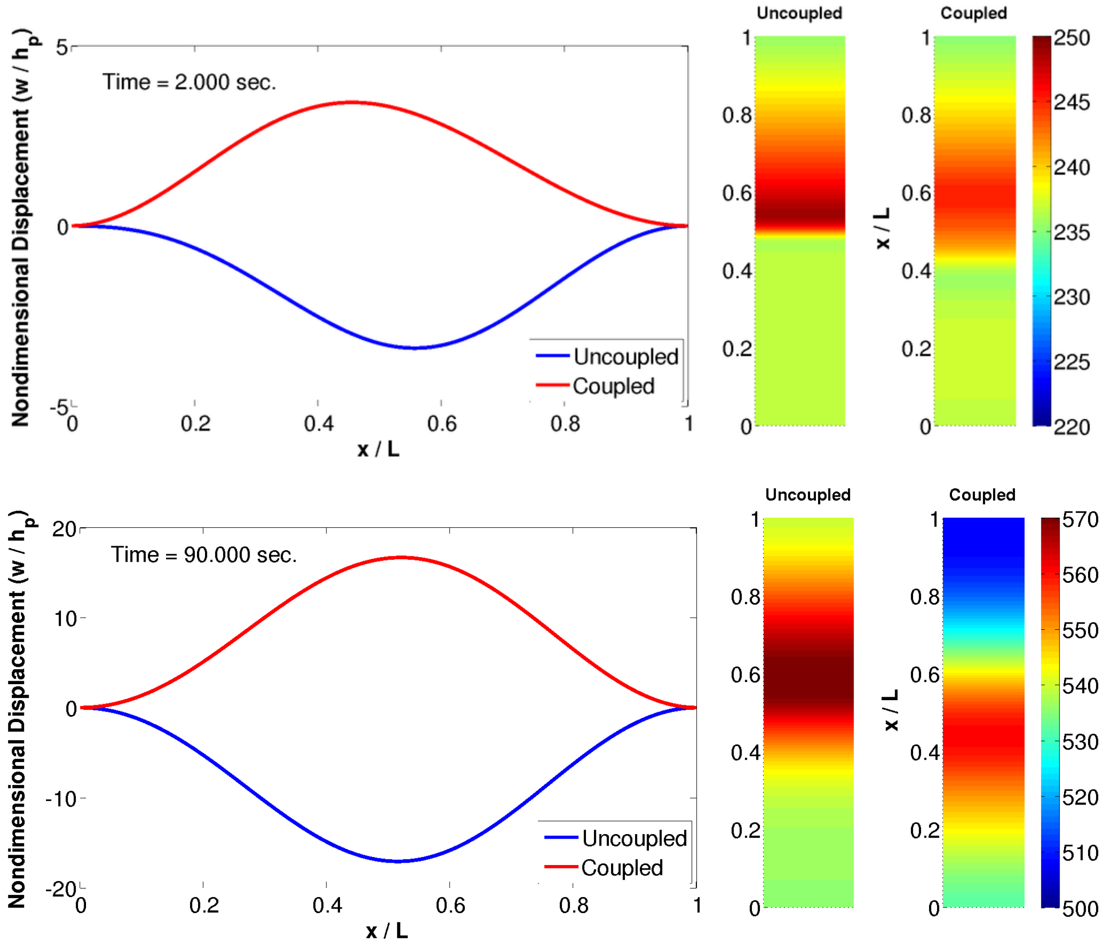
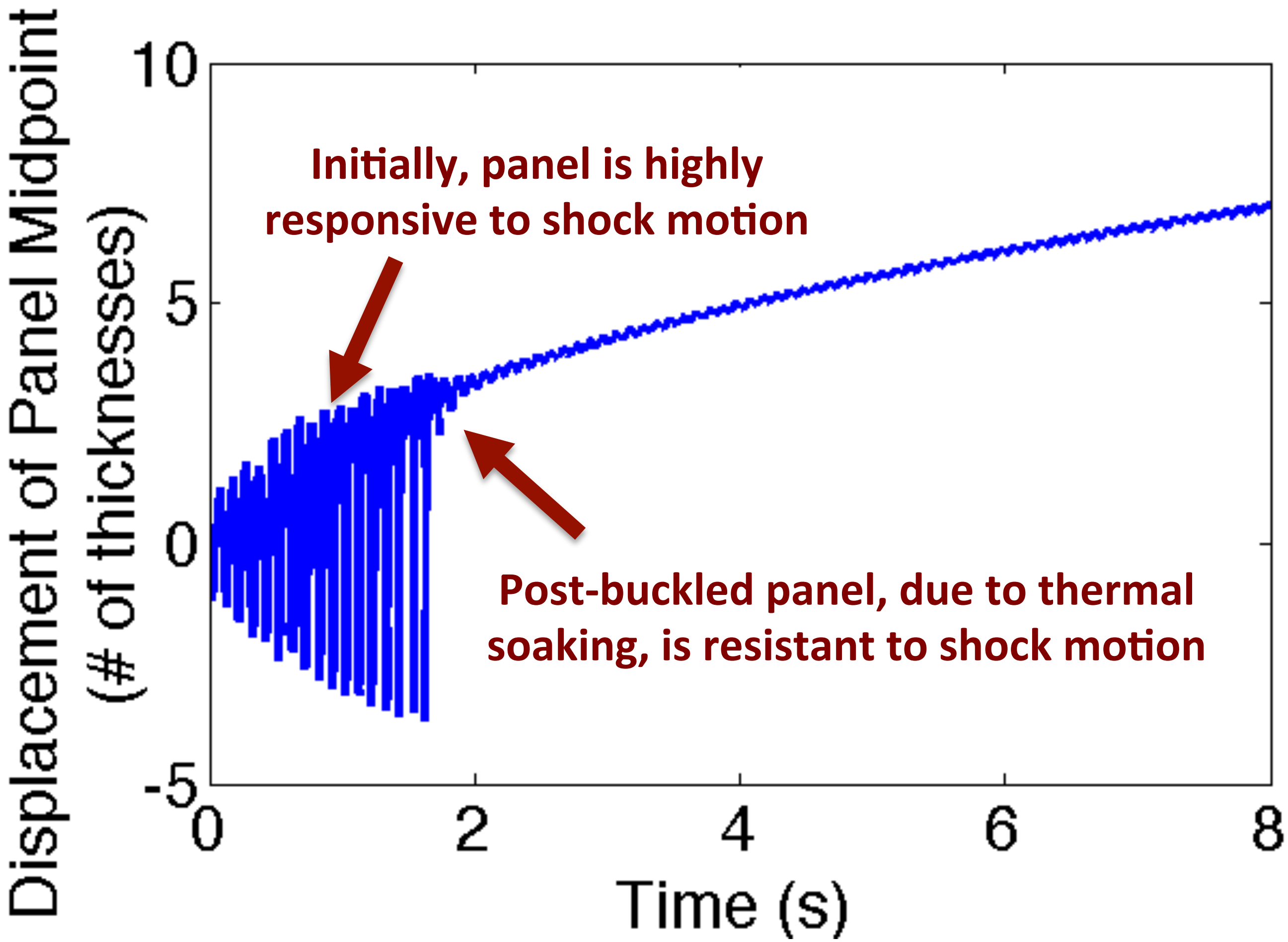
Thermo-Mechanical Response

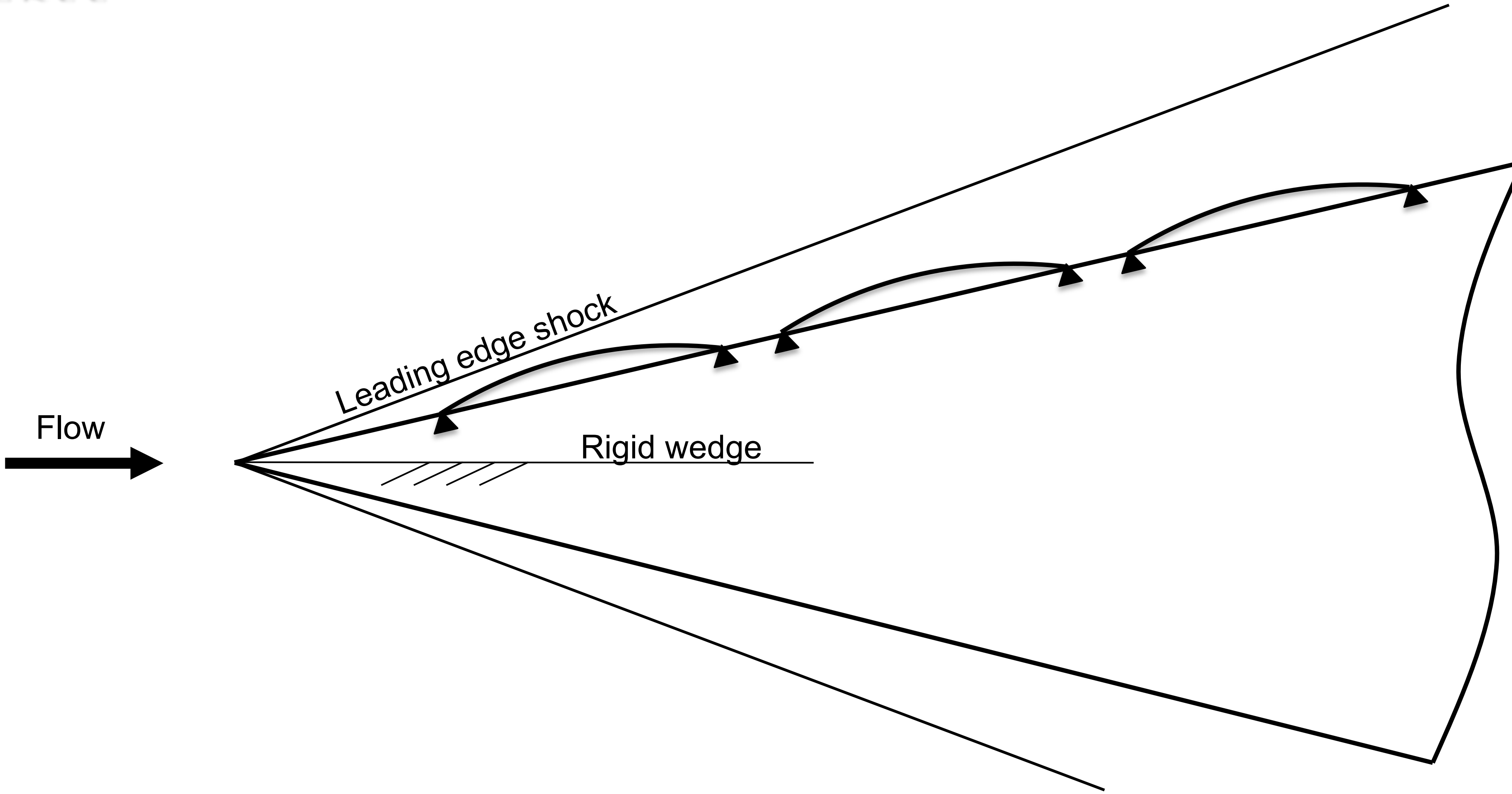


Temperature (K)

Mid-Point Displacement

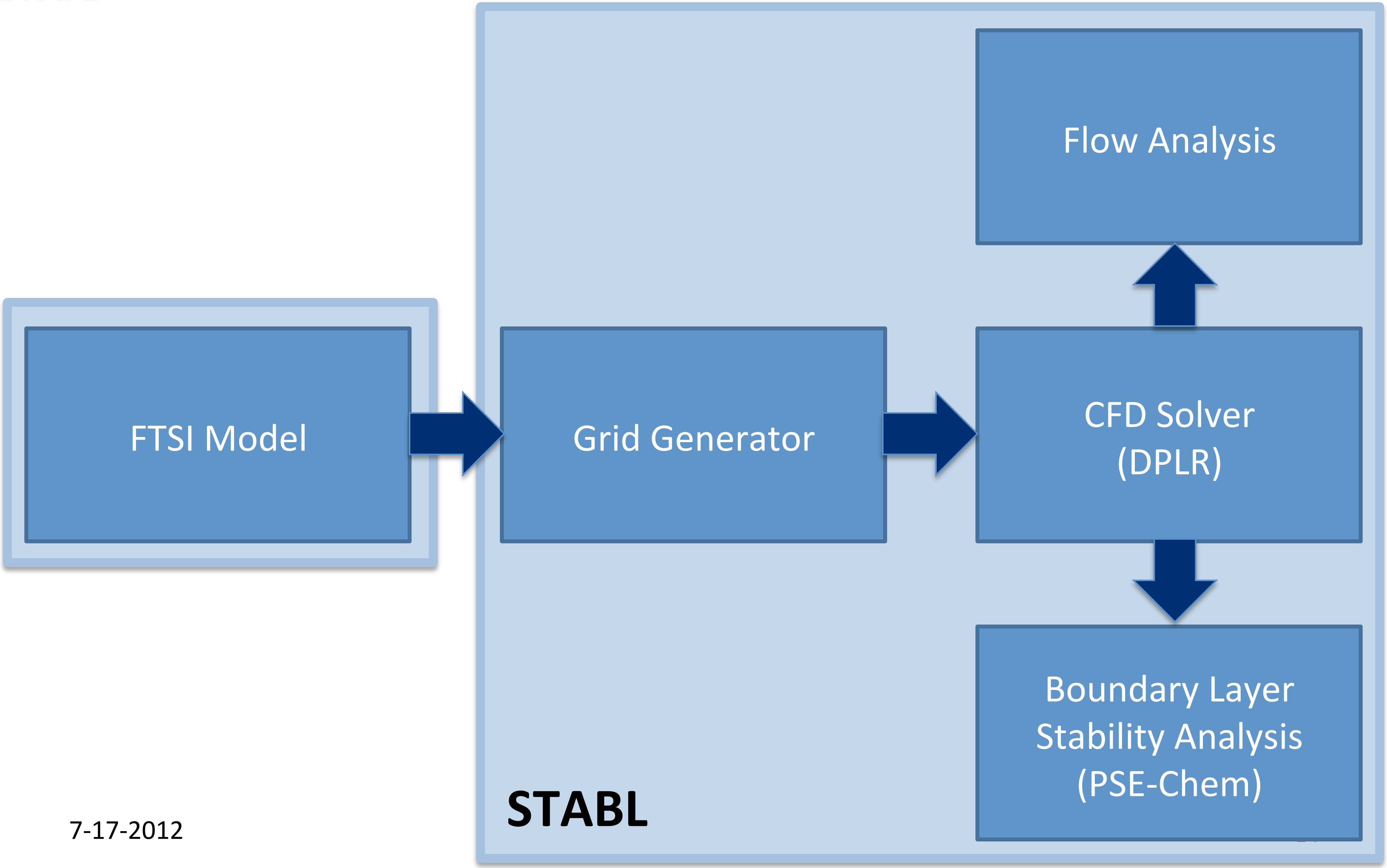


Impact of FTSI on HBLT & Stability



Riley, McNamara, Johnson "Hypersonic Boundary Layer Stability in the Presence of Thermo-Mechanical Surface Compliance," AIAA-2012-15489, 2012.

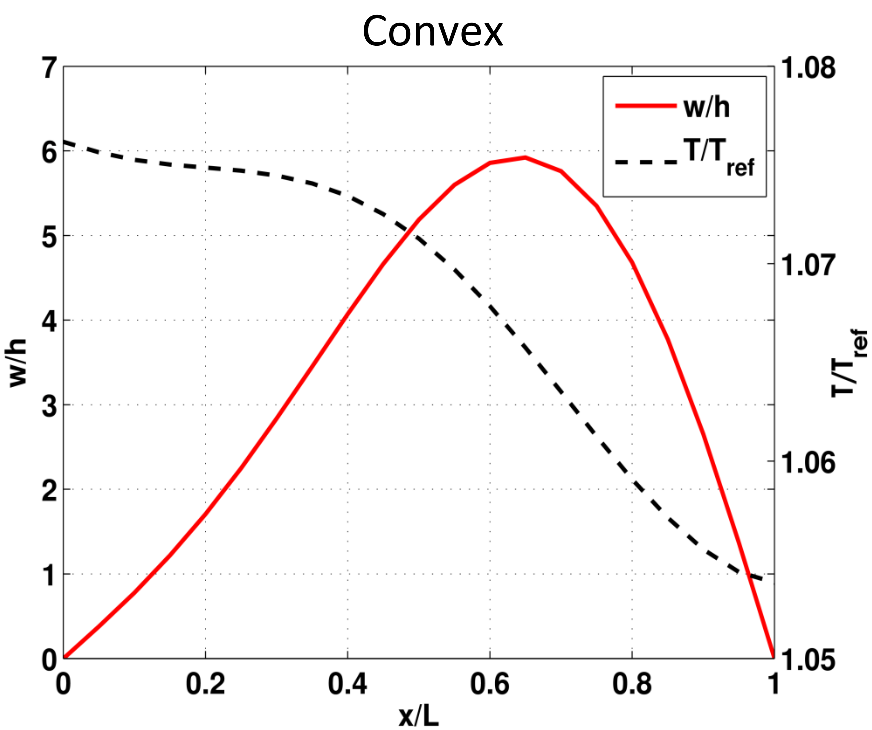
First Order Analysis

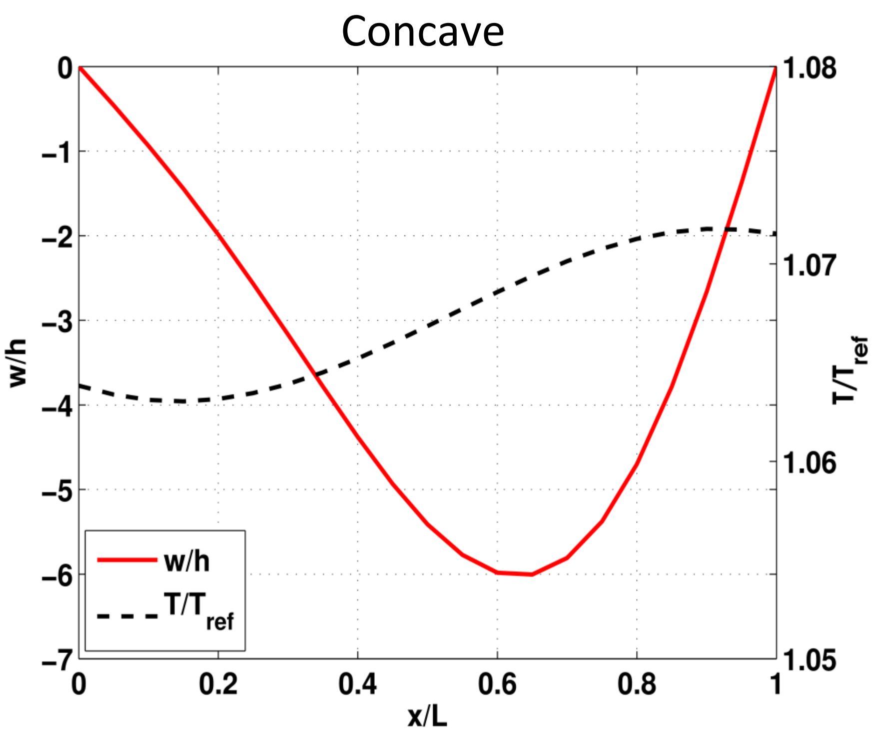


7-17-2012

Panel Response

- Response for Panel Location and Multiple Panel studies
- Max displacement ~6X panel thickness
  - 3X (1m), 1.8X (3m), 1.4X (5m) and 1.2X (7m) BLT of rigid wedge
- Max temperature ~7% higher than isothermal temperature (300K)





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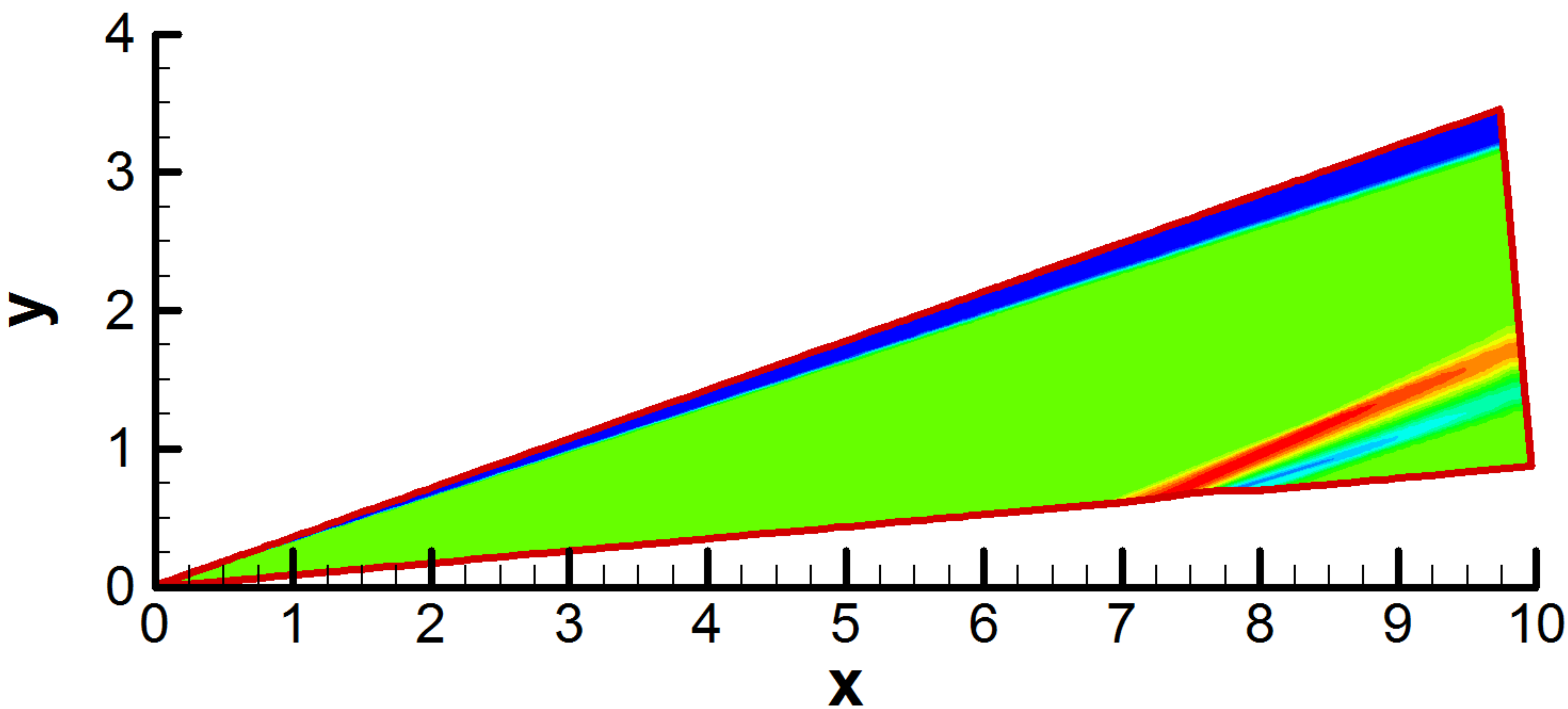
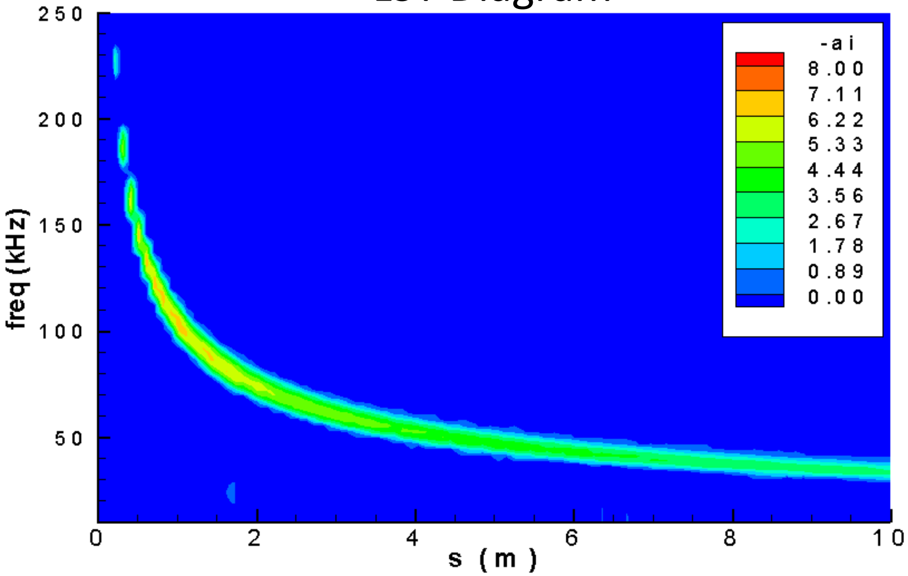
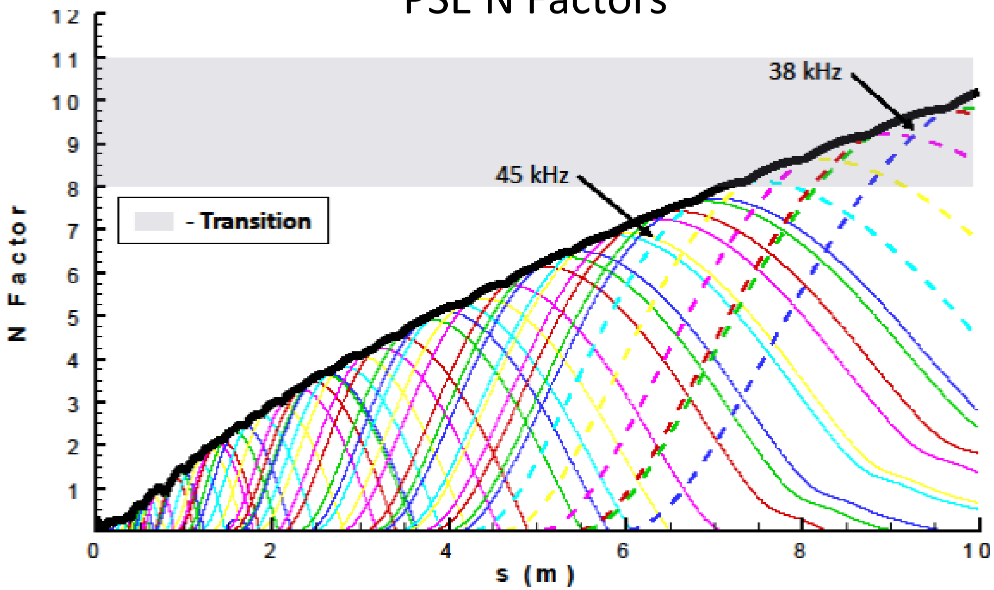


Rigid Wedge

LST Diagram



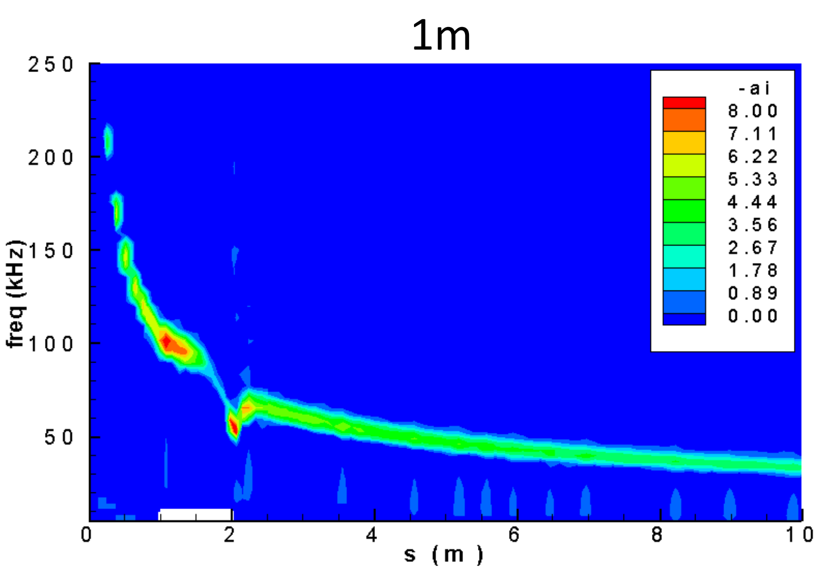
PSE N Factors

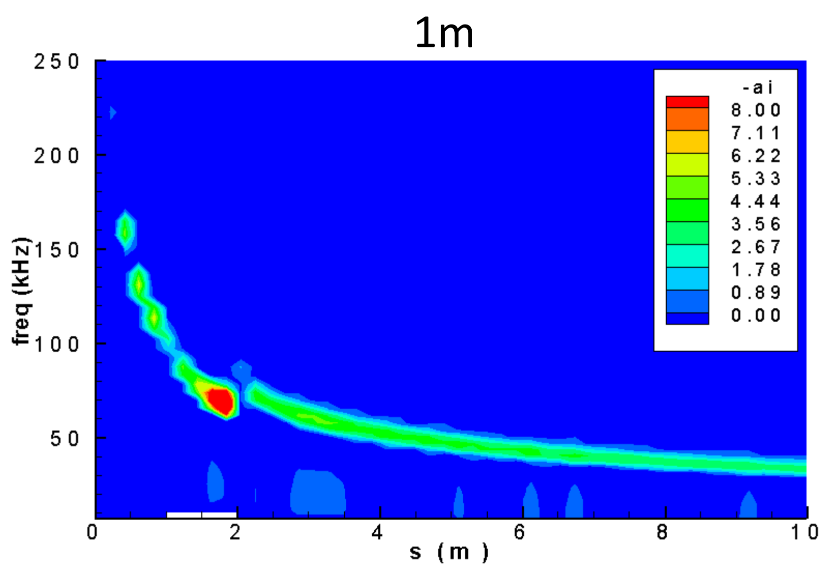


Study Parameters

Mach Number	4.0
Altitude	30 km
Wedge Half-Angle	5°
Wedge Length	10 m
Panel(s) Length	1 m

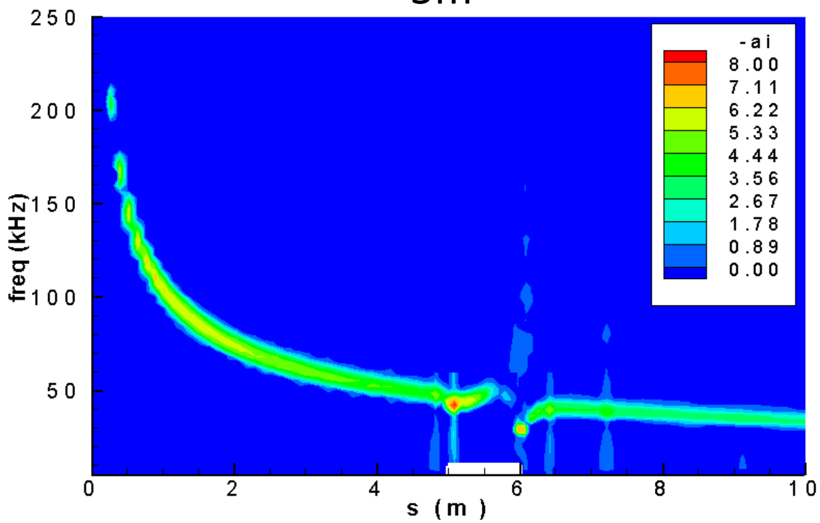
Single Panel – Varied Location



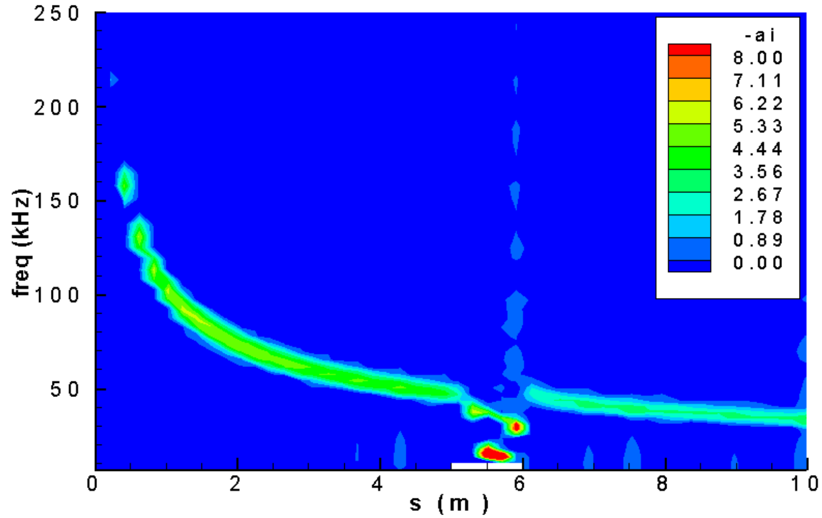


Single Panel – Varied Location

5m

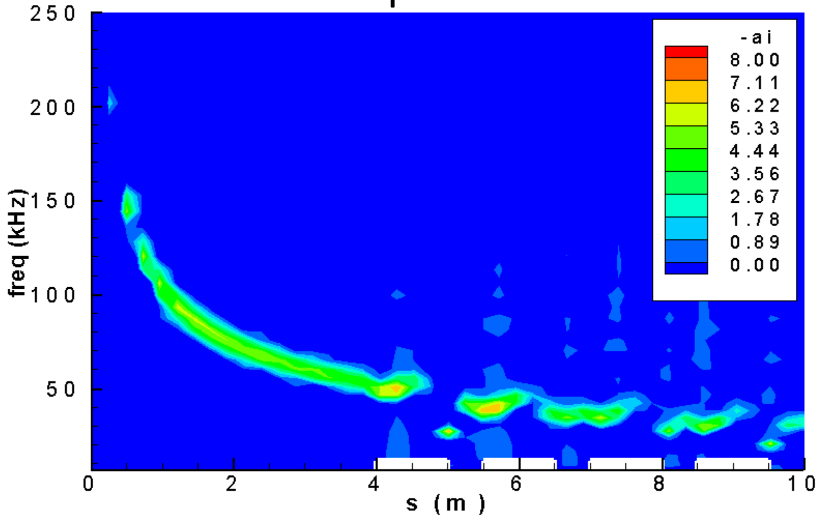


5m

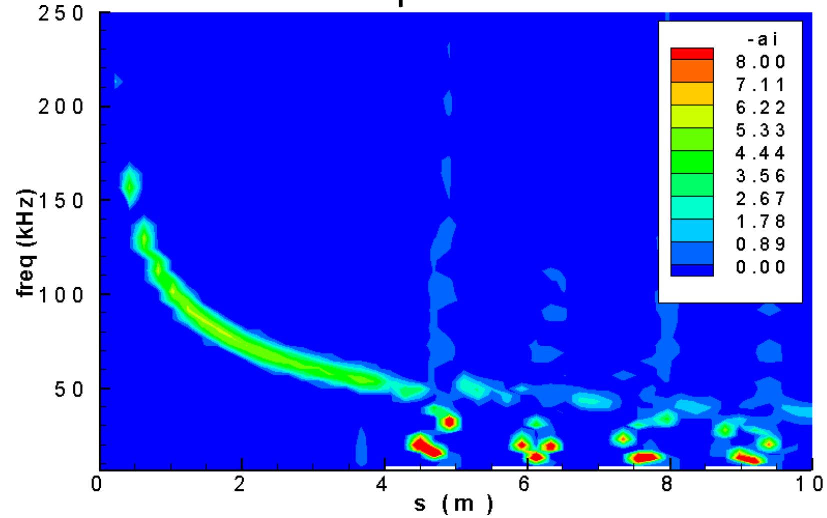


Single Panel – Varied Location

4 panels



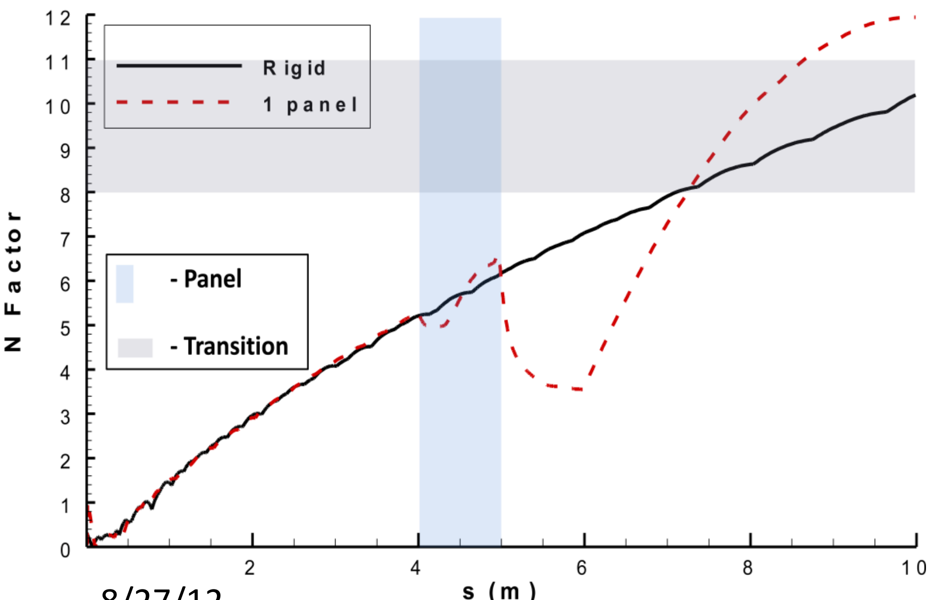
4 panels



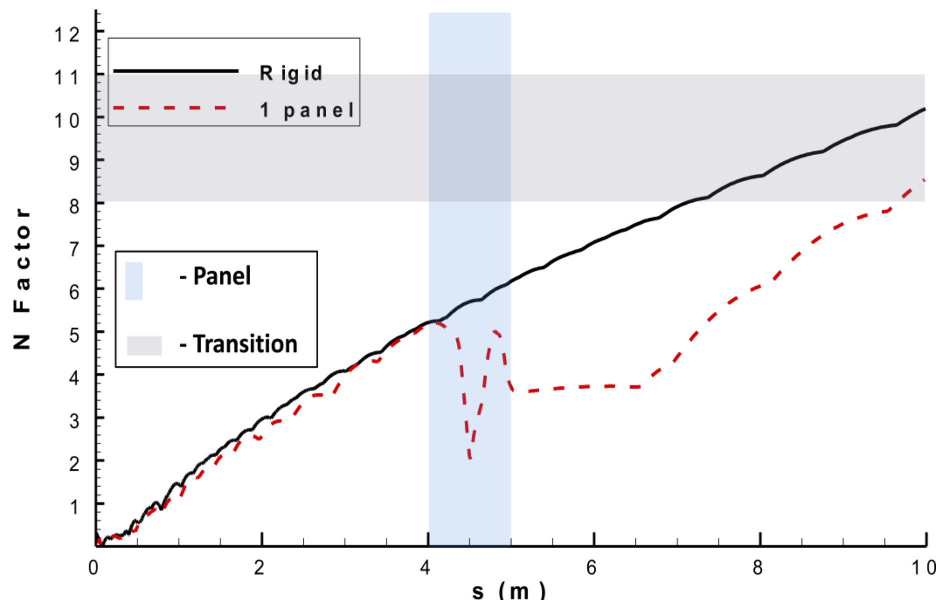
Multiple Panel PSE Results

Number of Panels	N_{max}	N_{max} Freq (kHz)	N_{tr} s(m)
Rigid	10.17	38.17	7.1-10
1	11.95	40.05	7.2-8.7

Number of Panels	N_{max}	N_{max} Freq (kHz)	N_{tr} s(m)
Rigid	10.17	38.17	7.1-10
1	8.39	16.67	--



Convex



Concave

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Number of Panels	N_{max}	N_{max} Freq (kHz)	N_{tr} s(m)
Rigid	10.17	38.17	7.1-10
1	11.95	40.05	7.2-8.7
2	12.06	37.47	8.2-9.4

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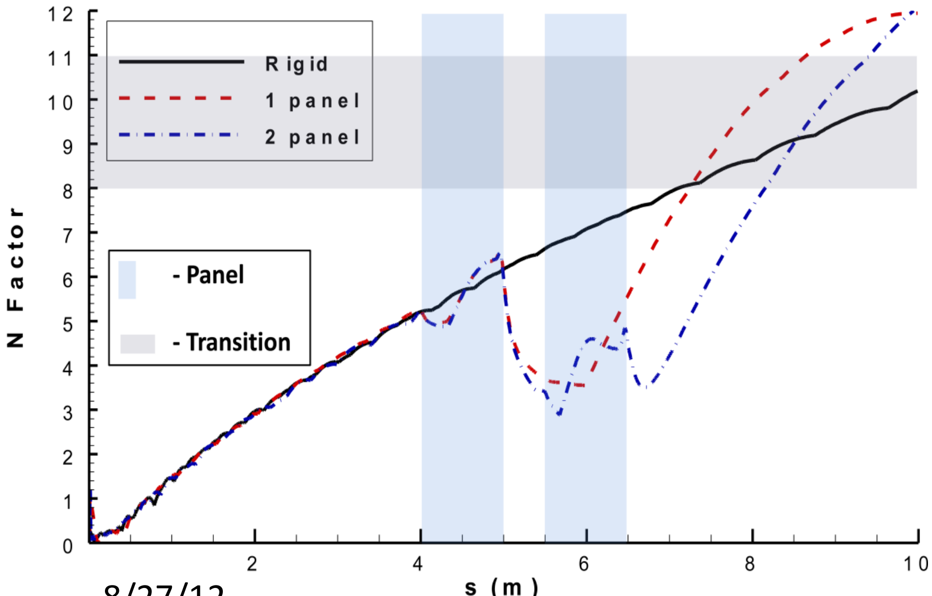
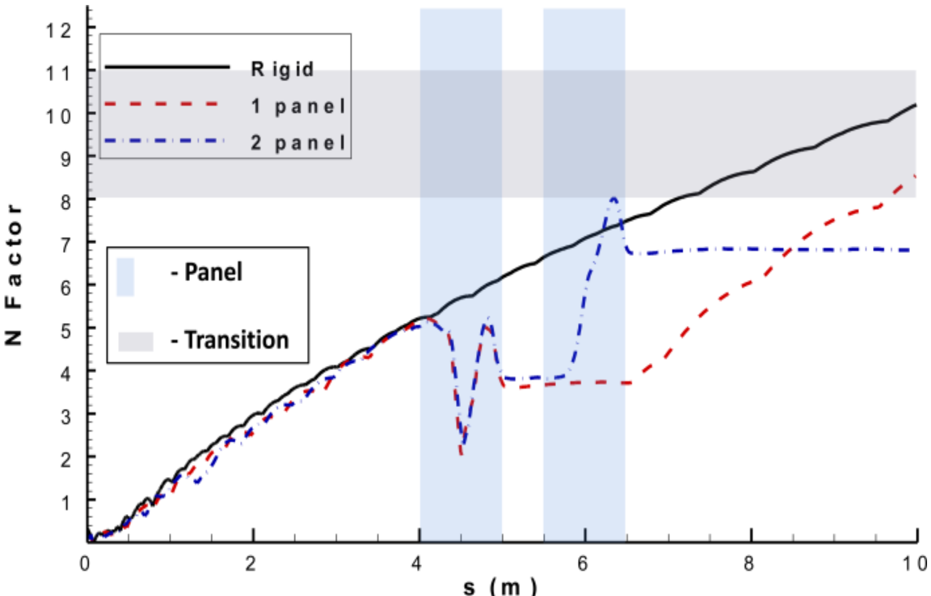
Rigid	10.17	38.17	7.1-10
1	8.39	16.67	--
2	7.98	16.67	6.33-6.35



Convex



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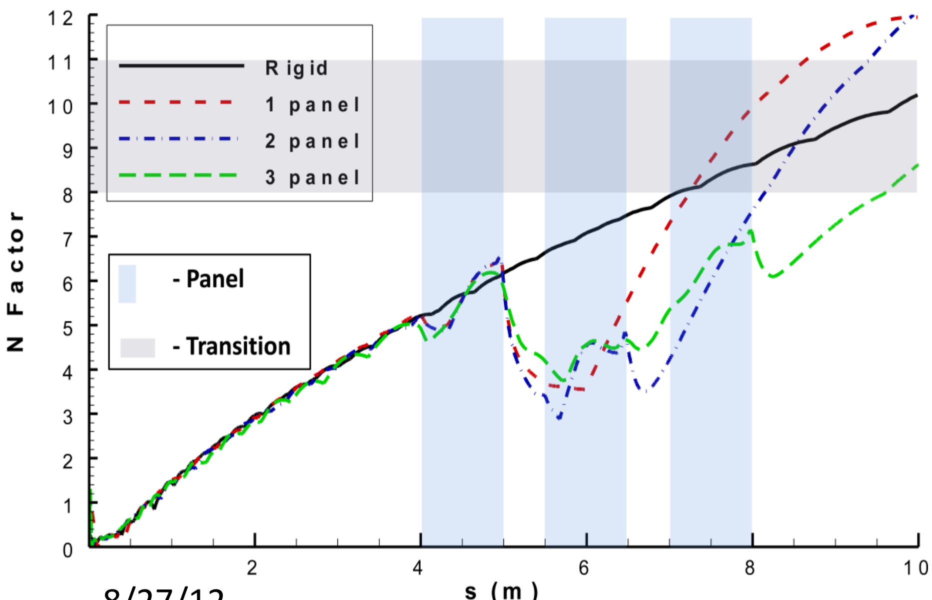
Rigid	10.17	38.17	7.1-10
1	11.95	40.05	7.2-8.7
2	12.06	37.47	8.2-9.4
3	8.59	37.11	9.6-10.0

Number of Panels	N_{max}	N_{max} Freq (kHz)	N_{tr} s(m)
Rigid	10.17	38.17	7.1-10
1	8.39	16.67	--
2	7.98	16.67	6.33-6.35
3	10.39	16.01	7.41-10.0



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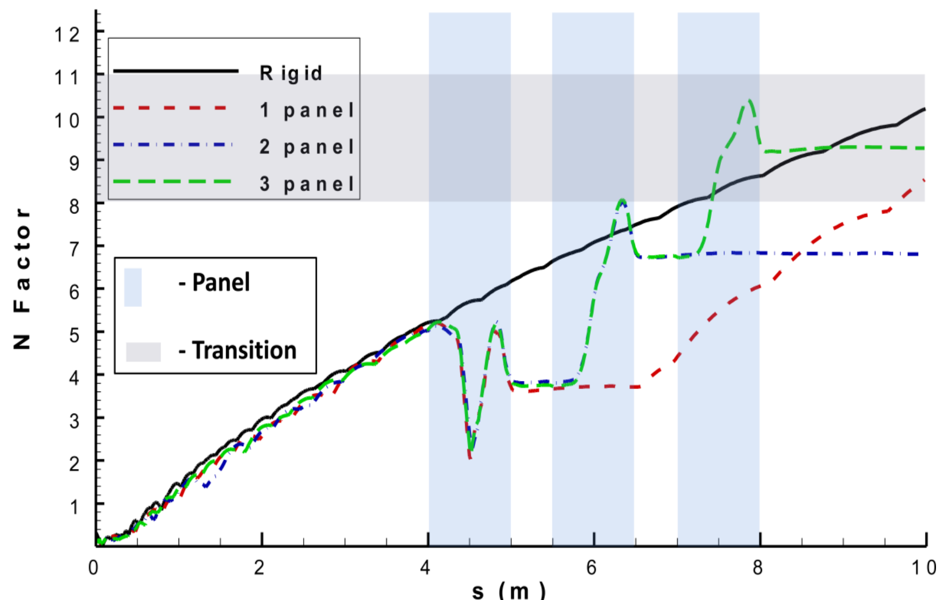

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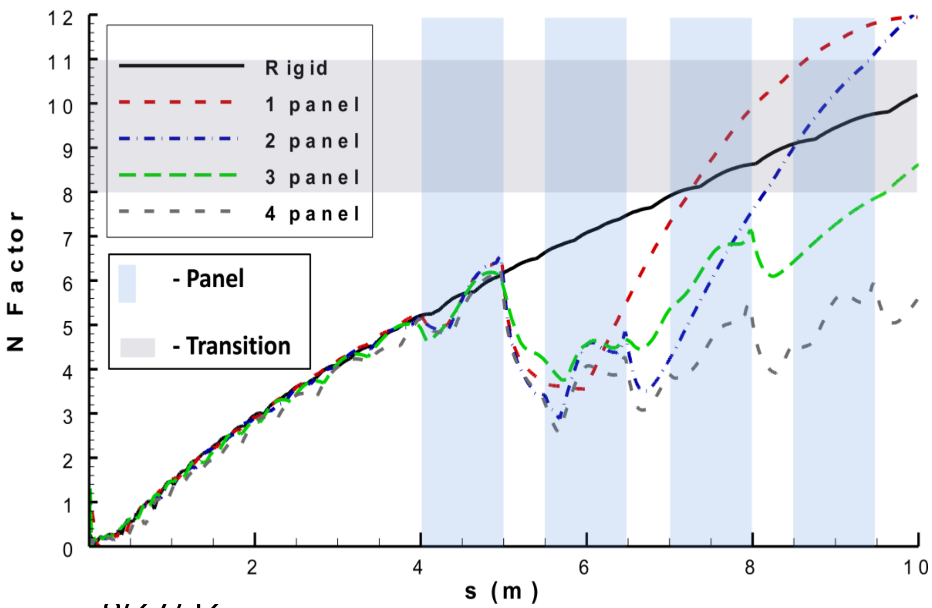
2	12.06	37.47	8.2-9.4
3	8.59	37.11	9.6-10.0
4	6.29	53.89	--

Number of Panels	N_{max}	N_{max} Freq (kHz)	N_{tr} s(m)
Rigid	10.17	38.17	7.1-10
1	8.39	16.67	--
2	7.98	16.67	6.33-6.35
3	10.39	16.01	7.41-10.0
4	12.36	15.46	7.41-8.97



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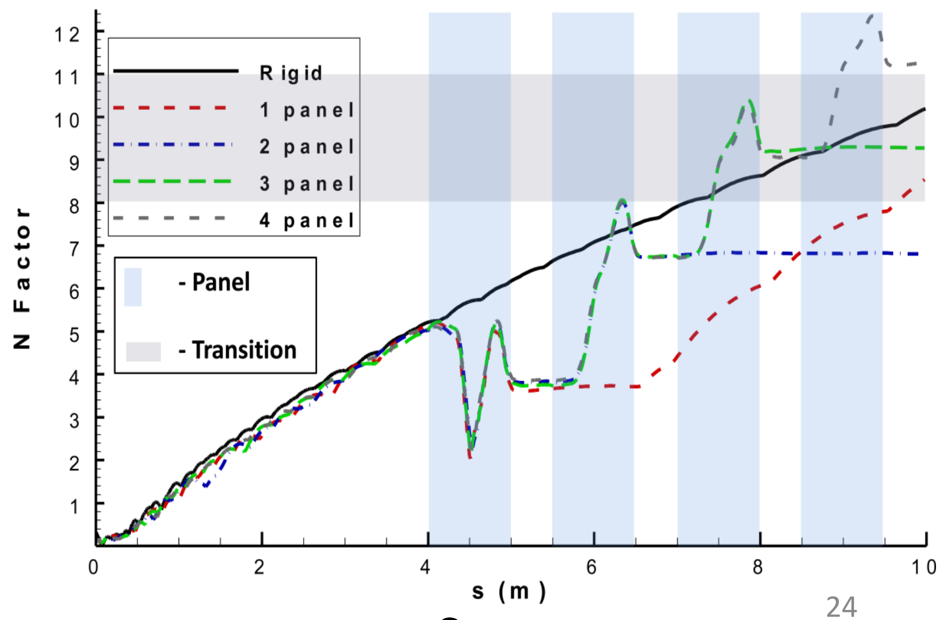

Concave

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Fundamental Questions & Challenges

- Bricks don't fly easily…but they sure are easier to design.
- Experimental validation of ***coupled*** physics?
- Incorporation of LES/DNS into ***long time record*** multi-physical analysis?
    - SBLIs
    - Turbulent Boundary Layer Loadings in General
- How does the N-factor corresponding to transition change with evolving surface conditions? What about 3-D considerations?
- Consequences of damage accumulation & material evolution?