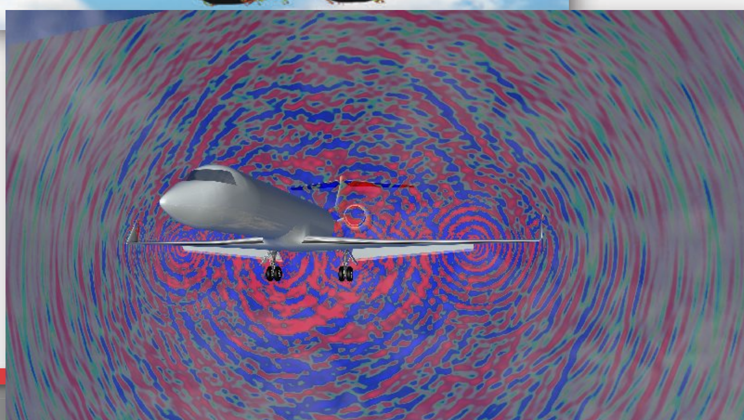


Recent Advances of the Lattice-Boltzmann Method for the Simulation of Transonic Flows

Swen Noelting

With contributions from : Hudong Chen, Raoyang Zhang, Pradeep Gopalakrishnan, Yanbing Li et al

Ehab Fares, Damiano Casalino, Benedikt König, Benjamin Duda, André Ribeiro et al

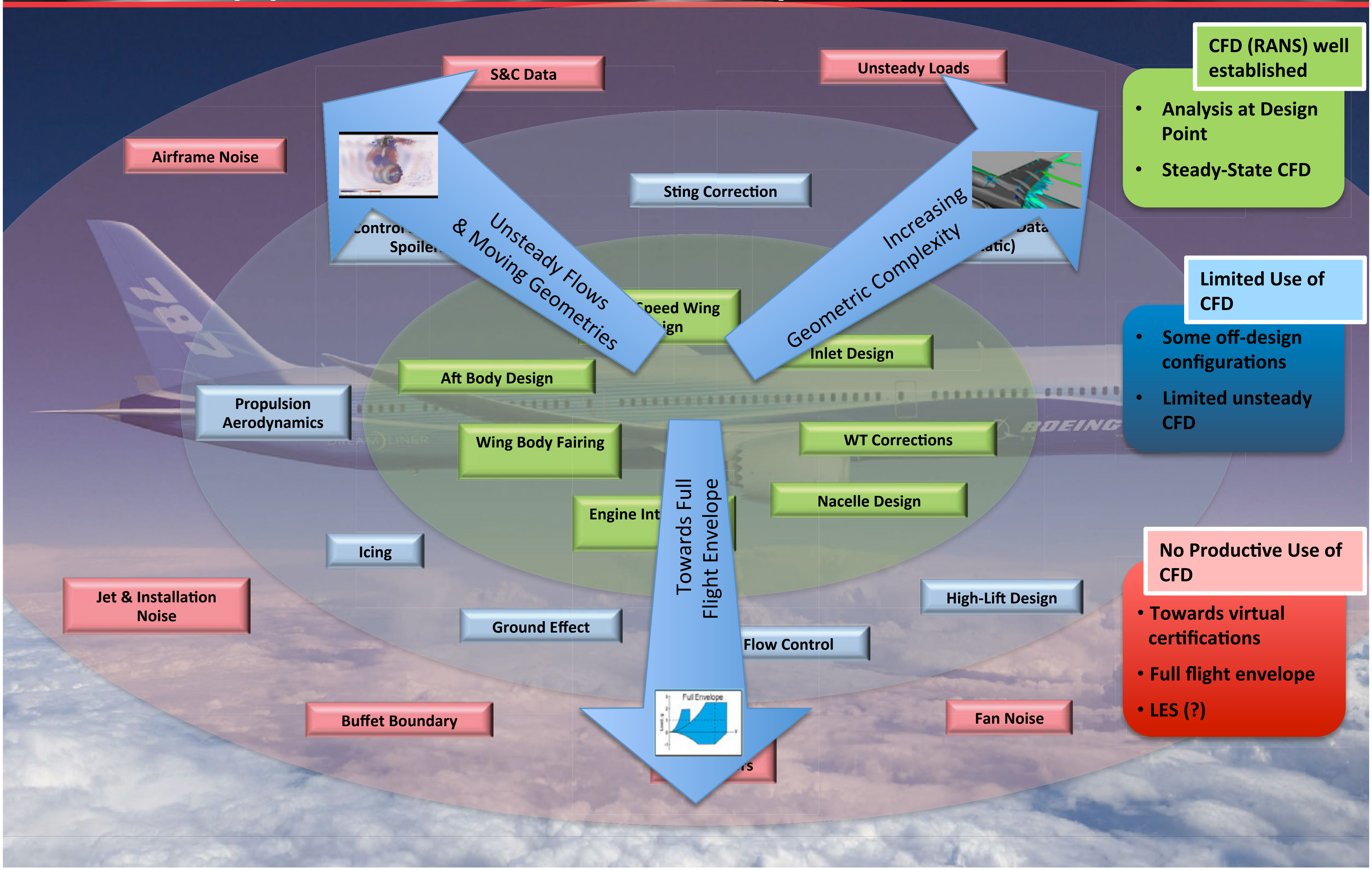
Applied Modeling & Simulation (AMS) Seminar Series

May 10, 2016

Outline

- Motivation: CFD Applications in Aerospace
- Overview of PowerFLOW Projects at NASA
- Theory & Background
  - *LBM*
  - *Turbulence model*
  - *Wall treatment*
  - *Extension to transonic flows*
- Transonic Code Validation and Application Examples
  - *Fundamental Validations*
  - *Industrial Application Examples*

CFD Applications in Aerospace



Motivation – Vision 2030

- CFD Vision 2030
  - *2014 Report to NASA by Key Industry Players (Boeing, Lockheed, Pratt&Whitney,...)*
- Main challenges for CFD to move beyond current status:
  - *Efficient handling of unsteady turbulent flows with significant regions of separation*
  - *Mesh generation*
  - *Robustness and automation of CFD simulations*
  - *Efficient use of HPC infrastructure*
  - *Managing very large amounts of data*
  - *Multi-disciplinary analysis & optimization*
- Hybrid RANS-LES and wall-modeled LES seen as best prospects
- Can LBM provide a contribution to address these challenges?

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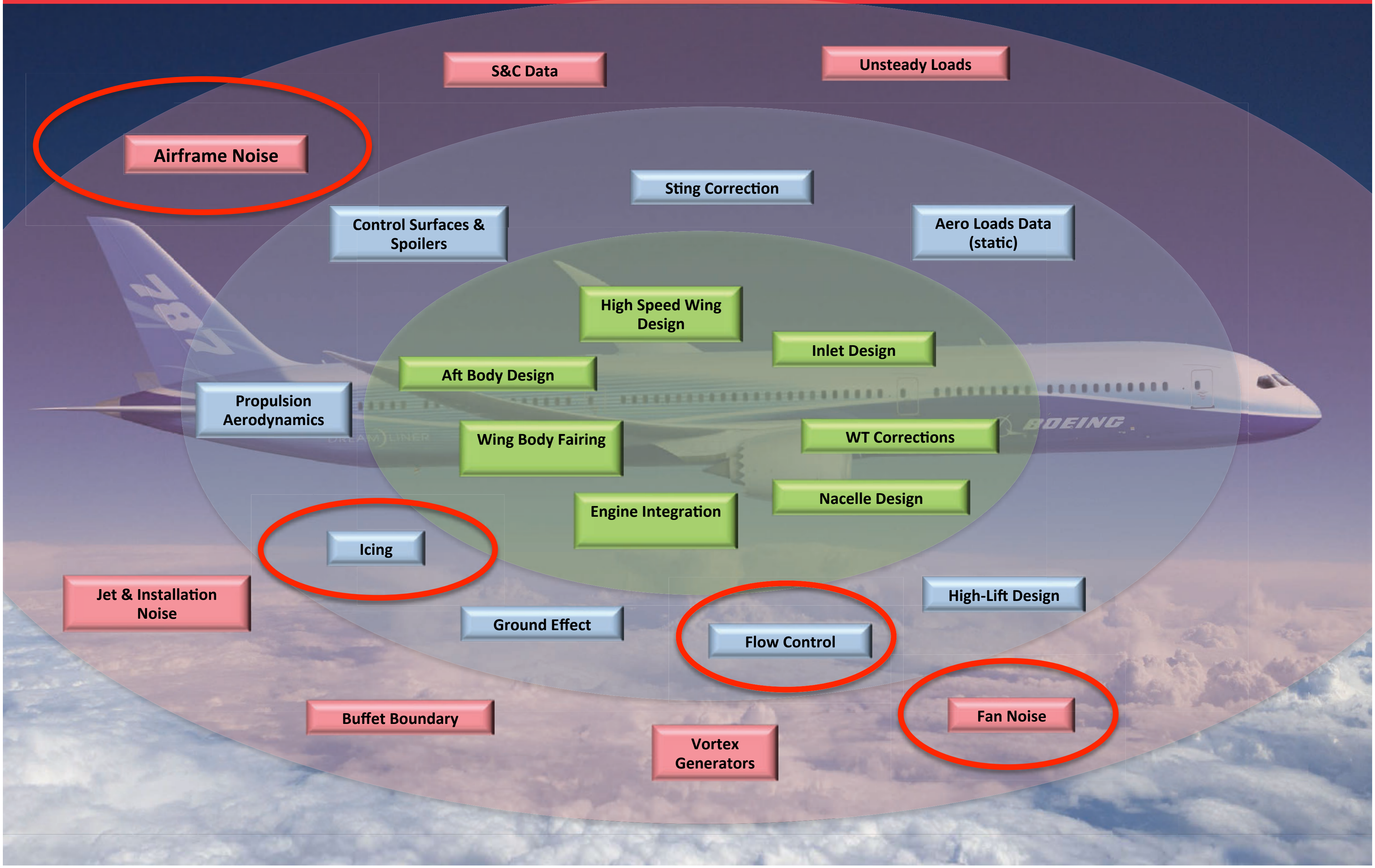
PowerFLOW Projects at NASA



Aeroacoustic Predictions

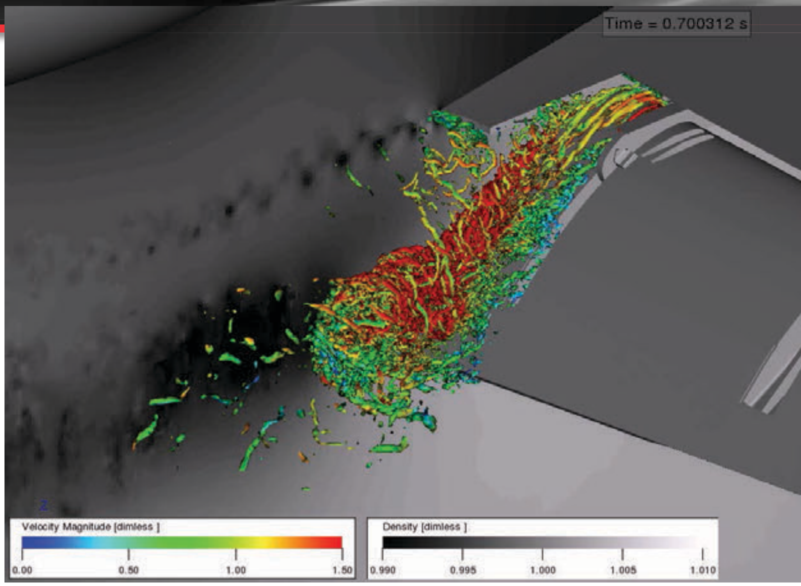
NASA ERA Project

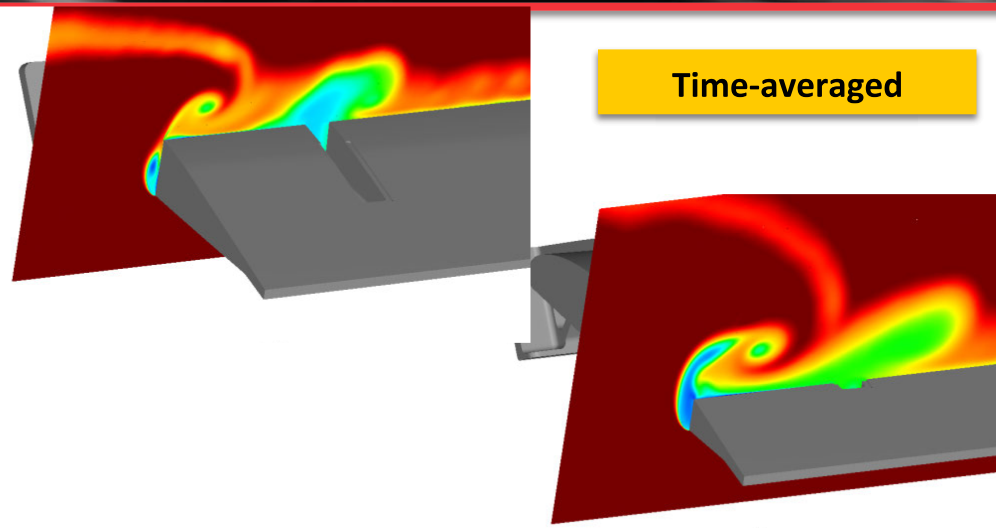
- **Simulation-based airframe noise predictions**
  - Simulated geometry: As–built 18% scale Gulfstream model
  - Baseline configurations
    - 39º flap deflection, main gear removed
    - 39º flap deflection, main gear deployed
  - Most flap and gear concepts simulated prior to wind tunnel testing
    - ROLD, FENoRFins, FLEXSEL, etc.
    - Solid and porous versions of knee, wheel, brake fairings
  - Sample quiet configuration
    - FENoRFins plus fully treated main gear

- **Accomplishments**
  - Predicted farfield noise for baseline and quiet configurations in good agreement with14x22 measurements
    - Established computational simulations as an accurate predictive tool
    - Paved the way for application to full-scale

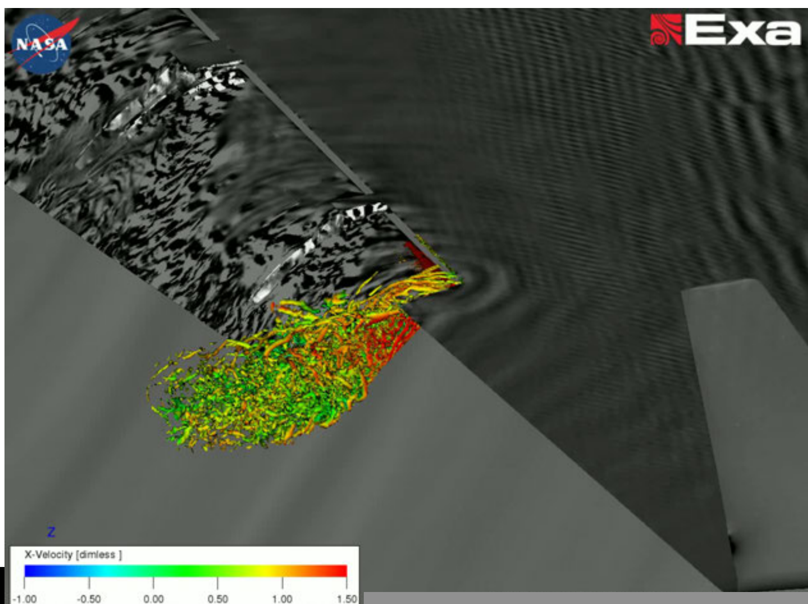
Airframe Noise – Flap Edge Noise

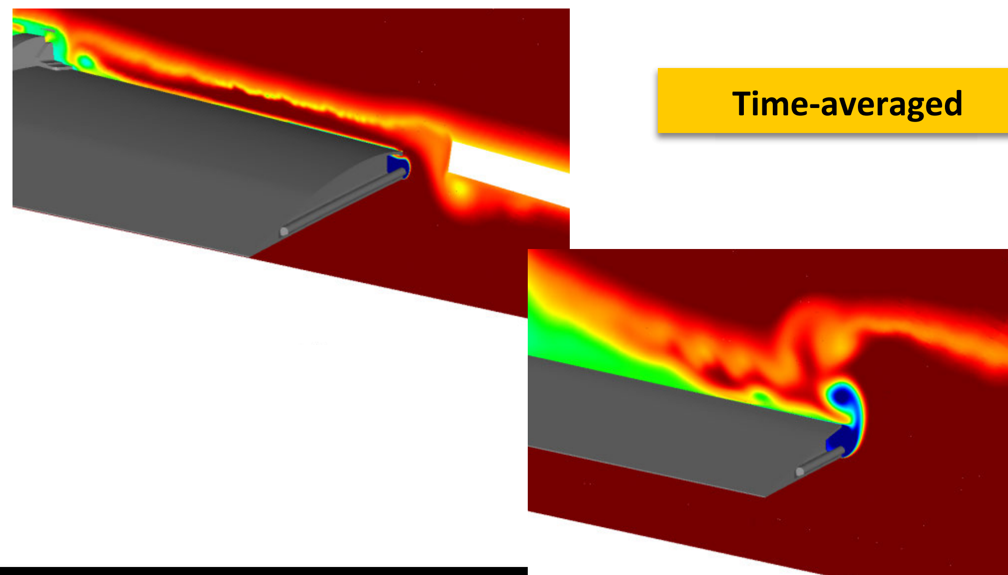
NASA ERA Project – G550





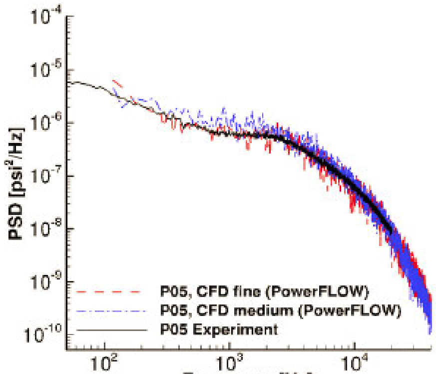
Time-averaged



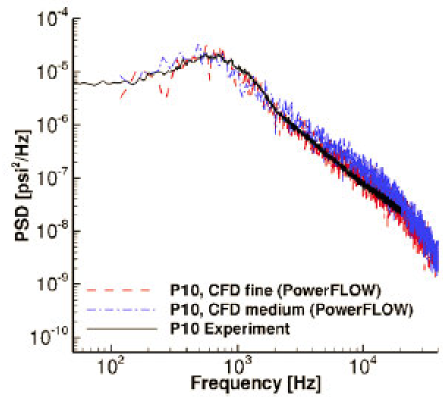


Time-averaged

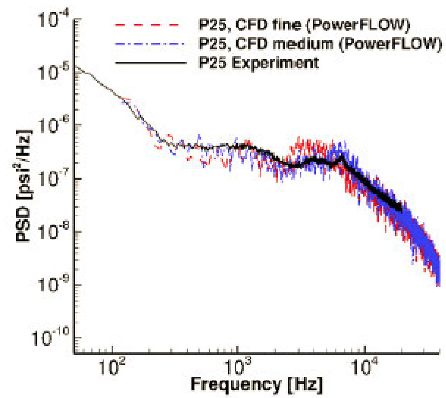
Airframe Noise – Flap Edge Noise



d) Probe 5 location



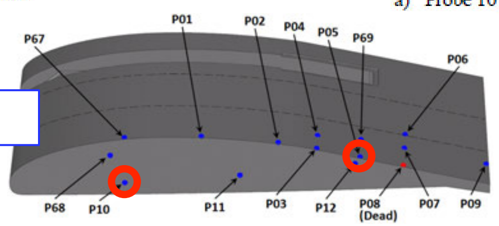
a) Probe 10 location

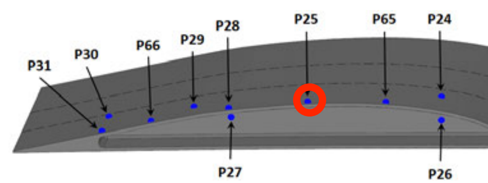


b) Probe 25 location

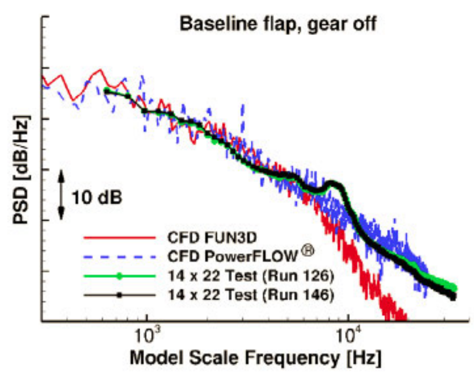
Surface Probes

Inboard Flap





Outboard Flap

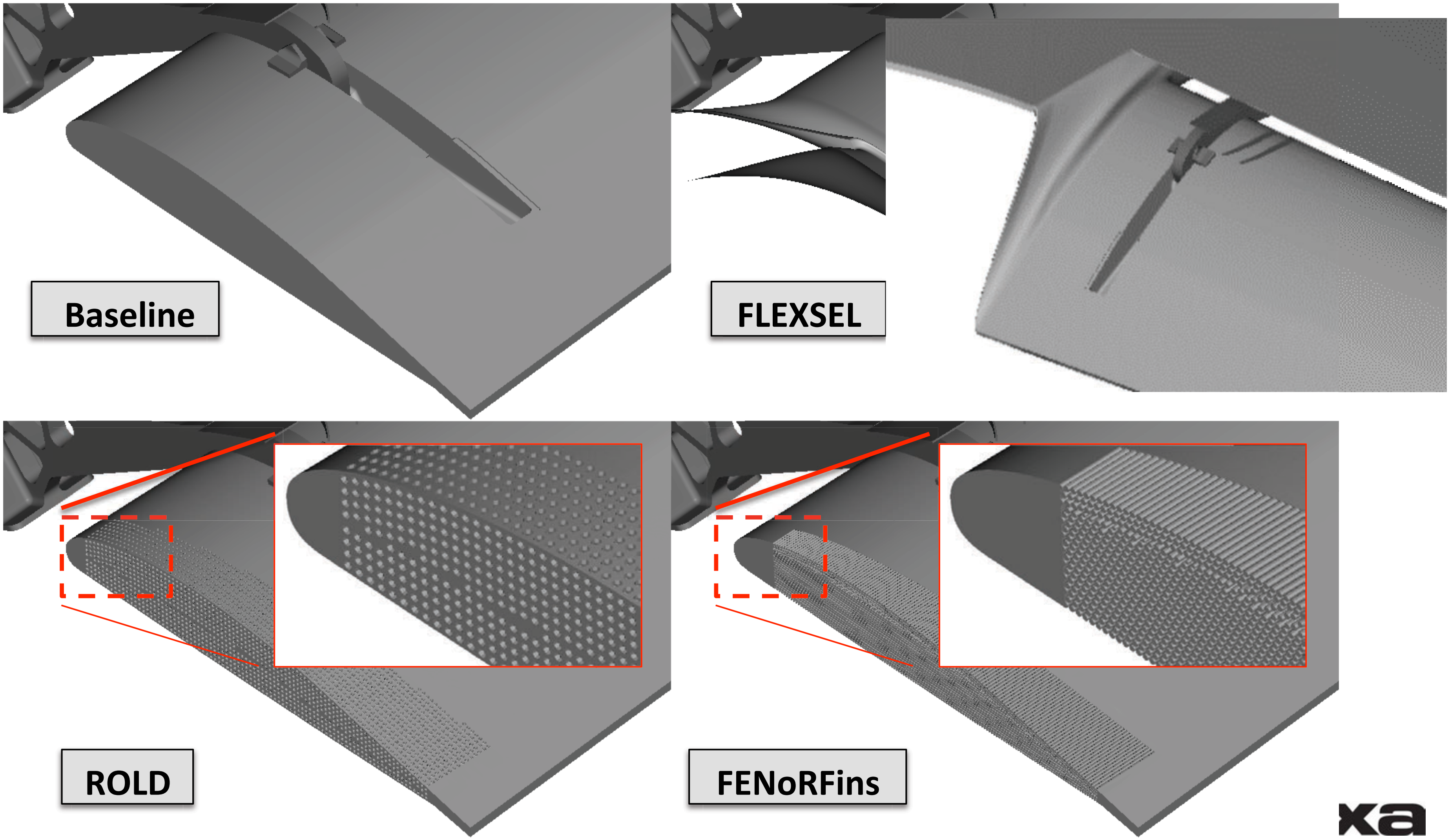


Far-Field Probes

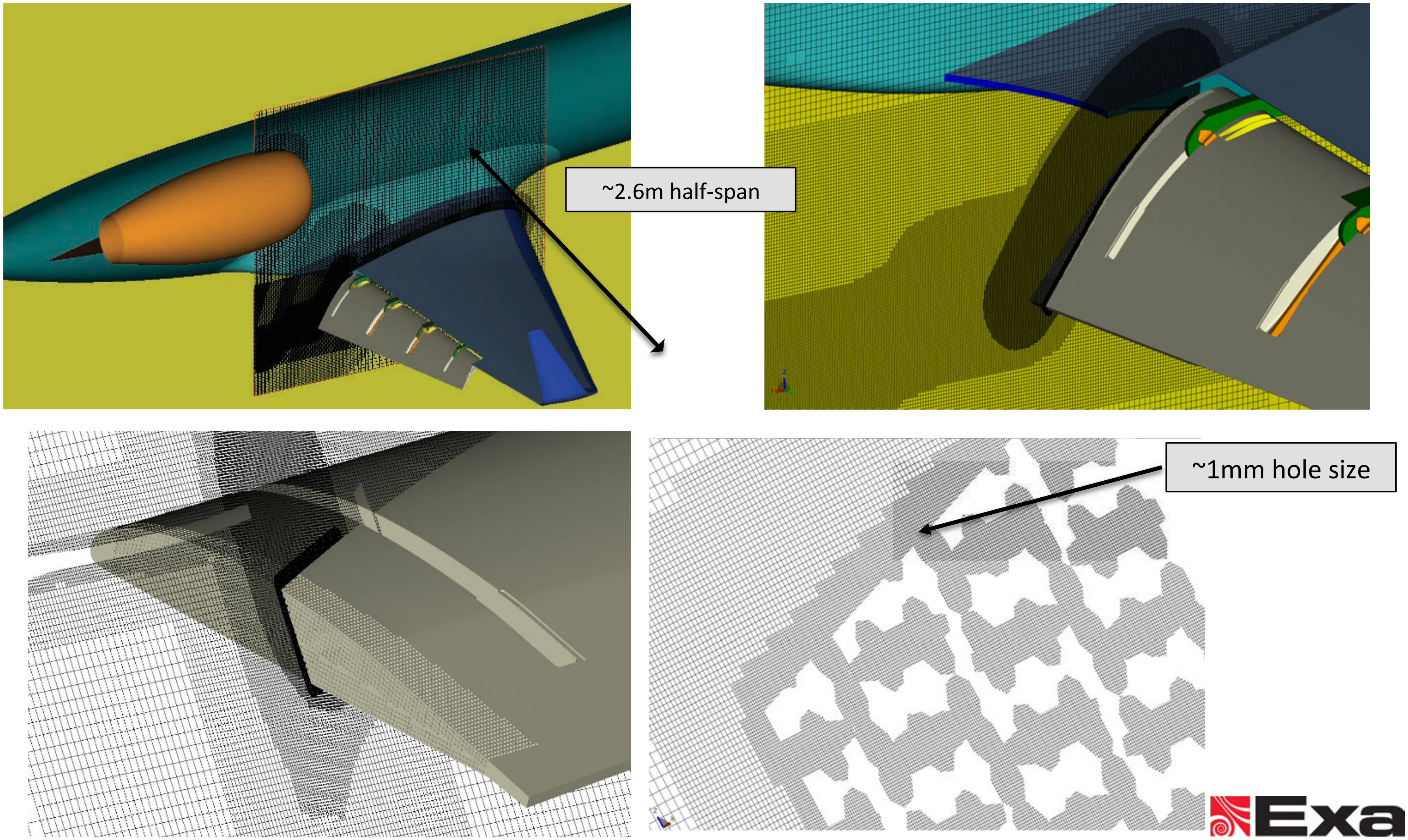
All simulations were carried out prior to wind tunnel tests

Exa

Airframe Noise – Noise Reduction Concepts

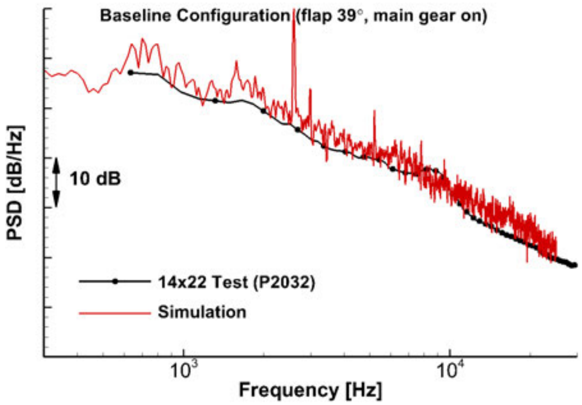


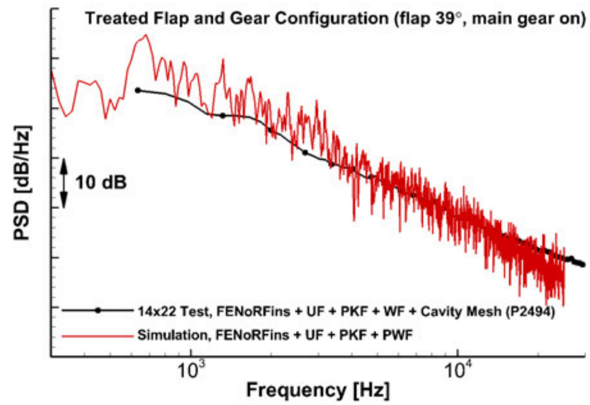
Computational Mesh

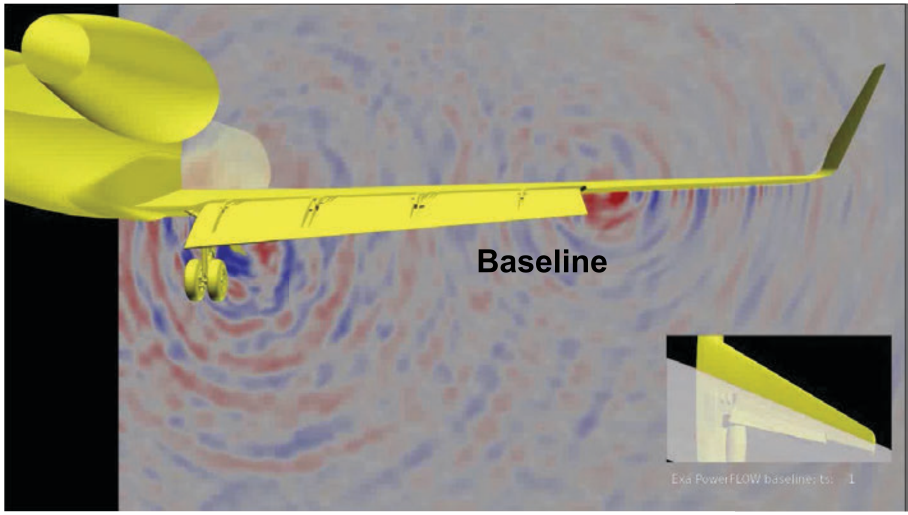


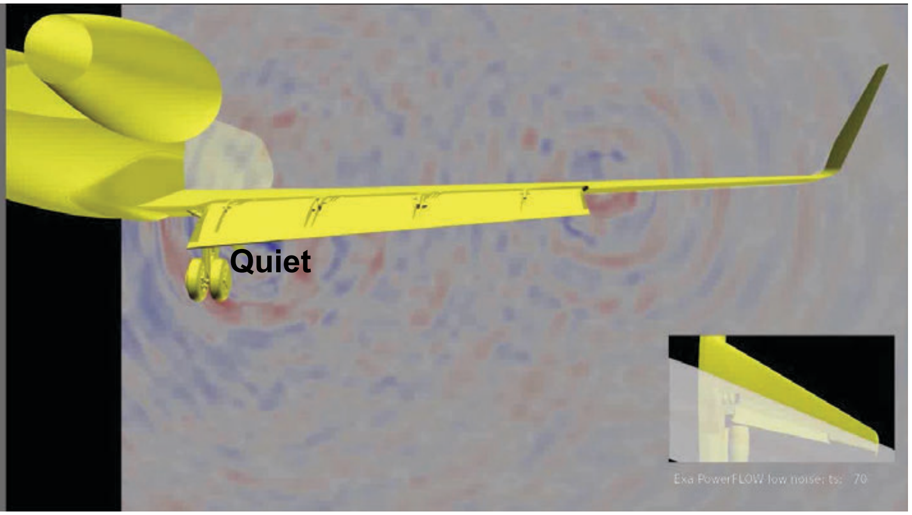
Baseline v. quiet Configurations

Flap 39º, main gear on configuration

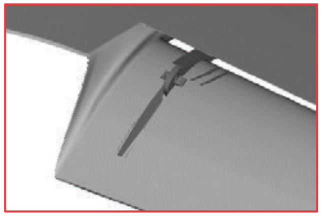




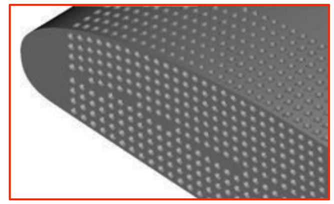




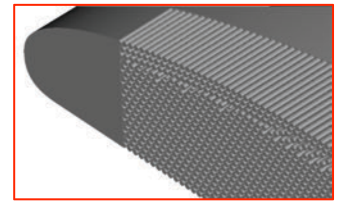
Flap Noise Reduction Concepts



FLEXSEL



ROLD



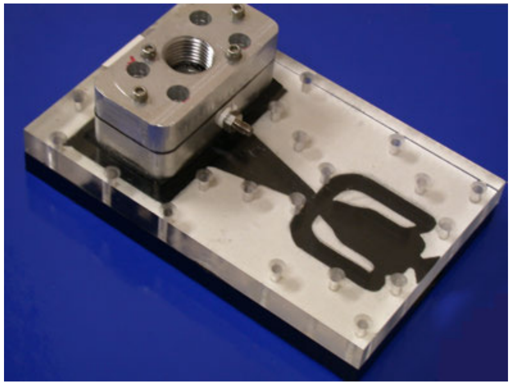
FENoRFINS

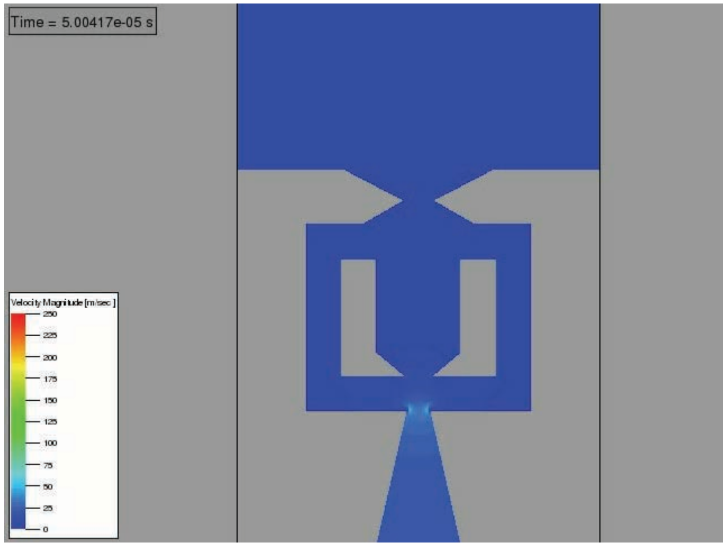
	Experiment 14x22 WT			PowerFLOW Simulations		
	FLEXSEL	ROLD*	FINS*	FLEXSEL	ROLD*	FINS*
(baseline – concept) OASPL [dB] (1kHz – 30kHz)	3.6	3.9	3.5	4.3	4.7	3.9

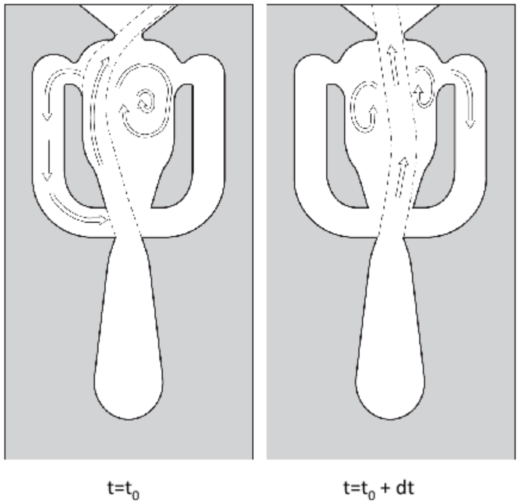
All simulations were carried out prior to wind tunnel tests

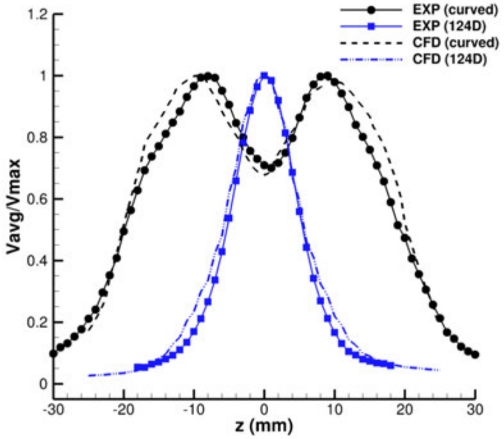
***The aerodynamic values shown here correspond to the smallest holes and fin diameter tested**

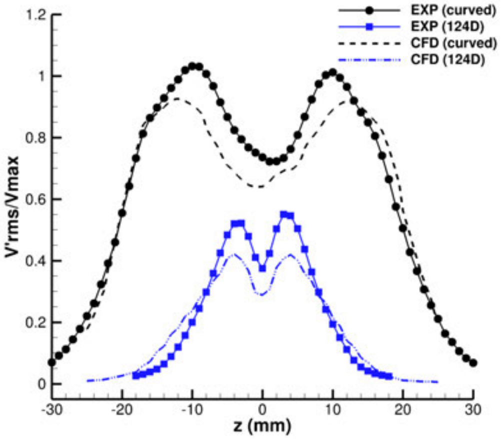
Flow Control





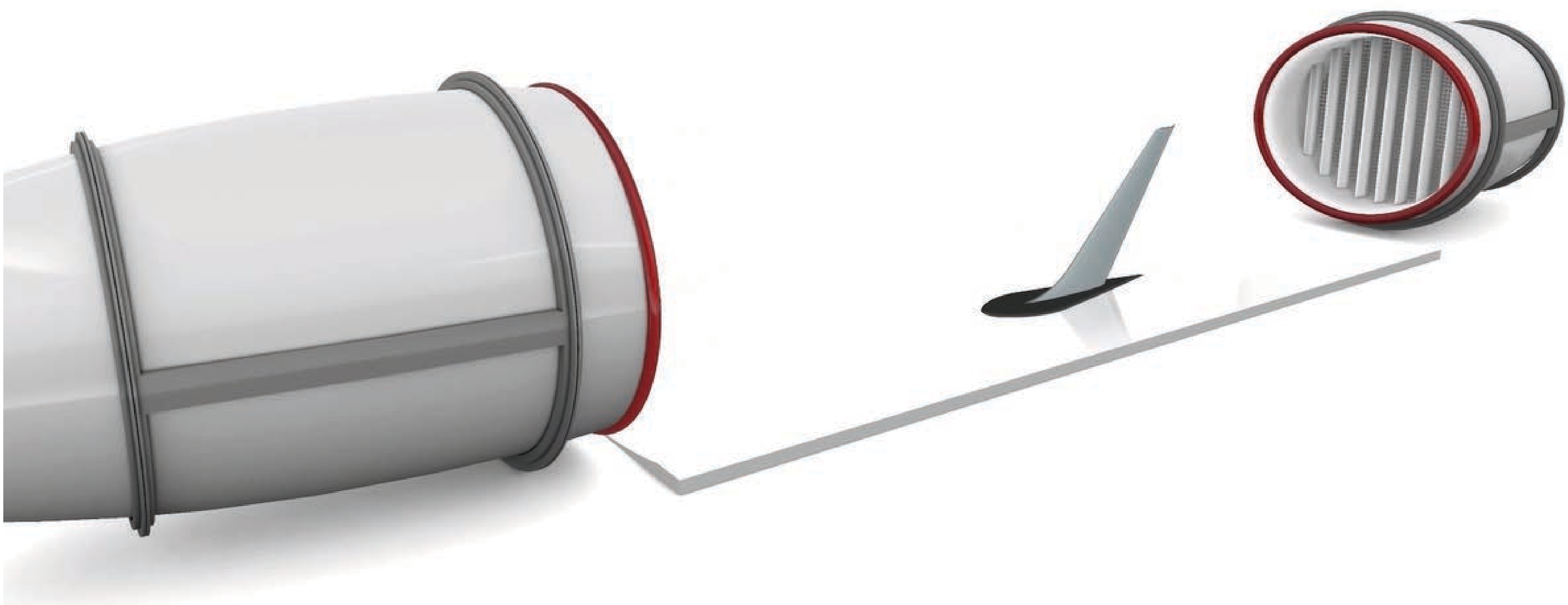




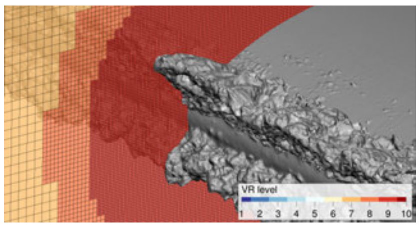


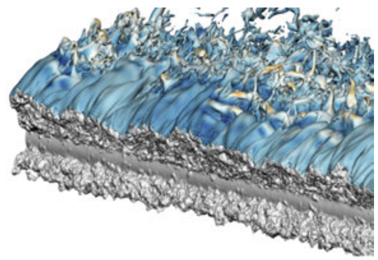
Source
AIAA 2012-3239

Tail Rudder with Active Flow Control

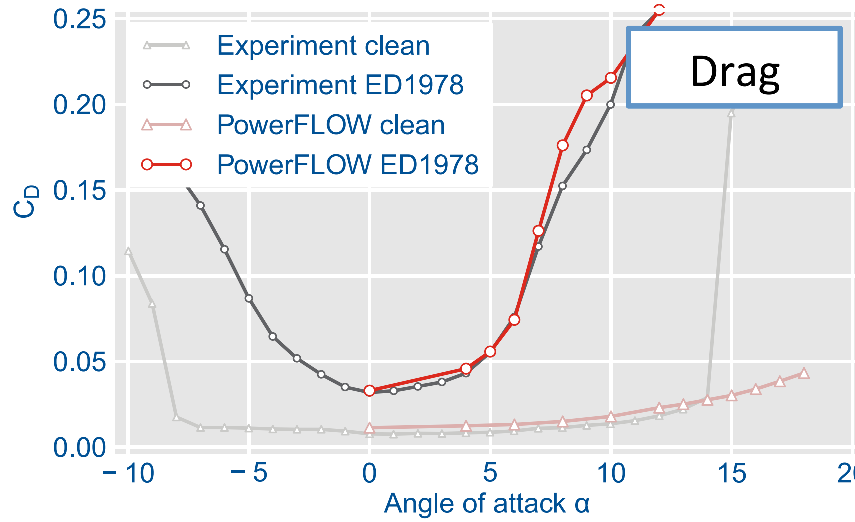


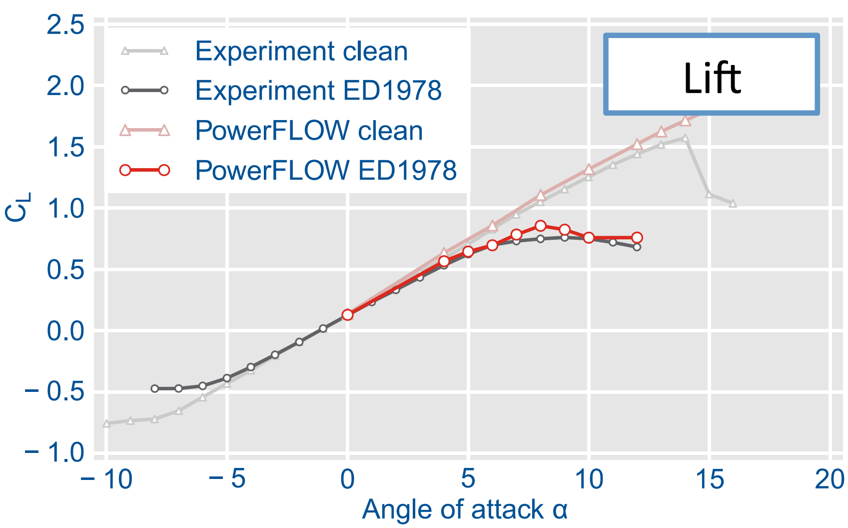
Aerodynamic Simulation of Realistic 3D Ice Shapes

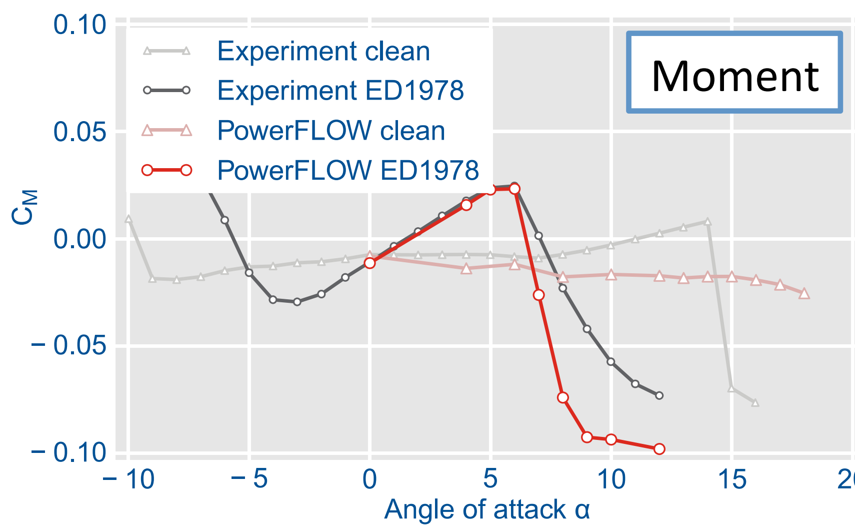




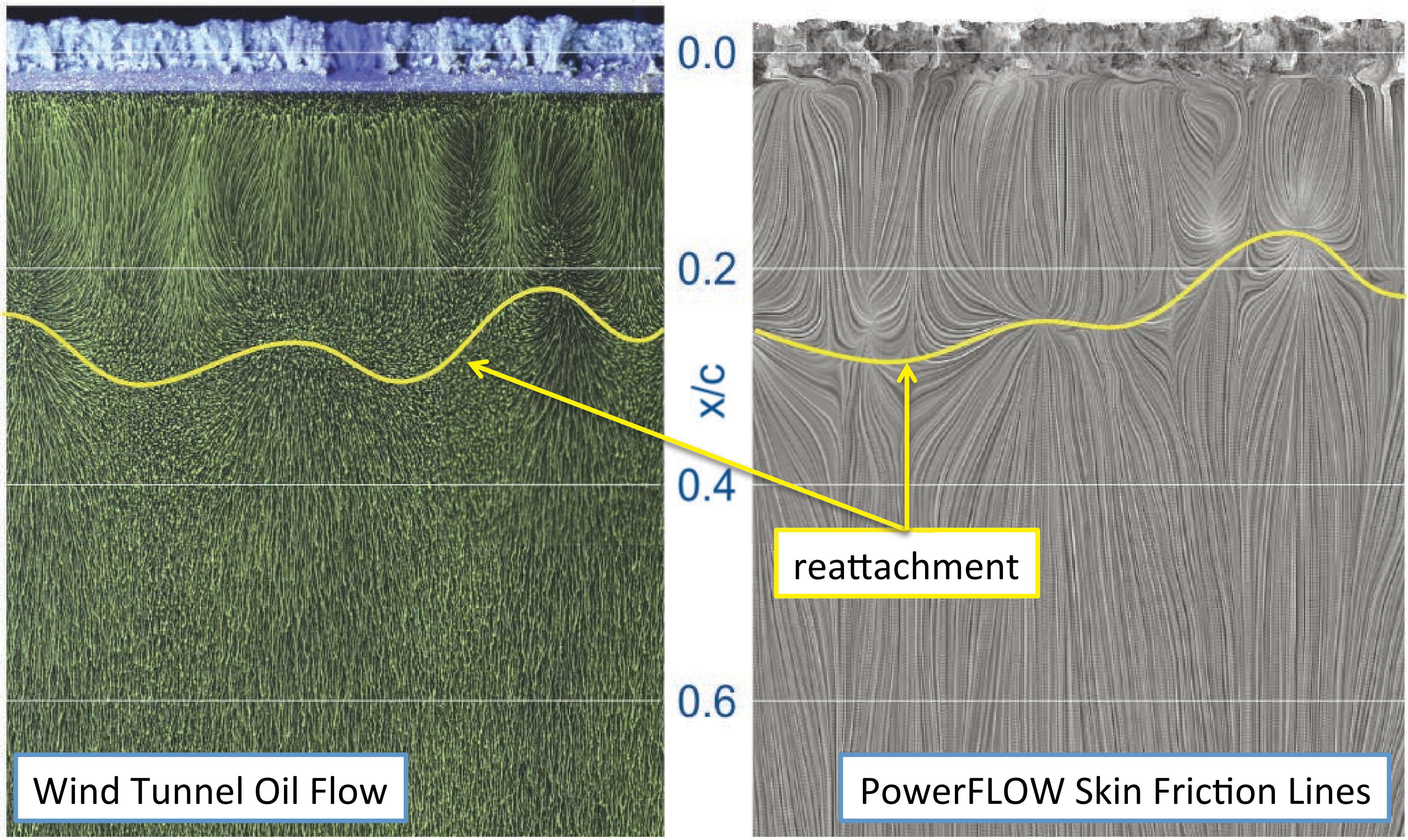
3D Ice Shapes provided by NASA/Glenn



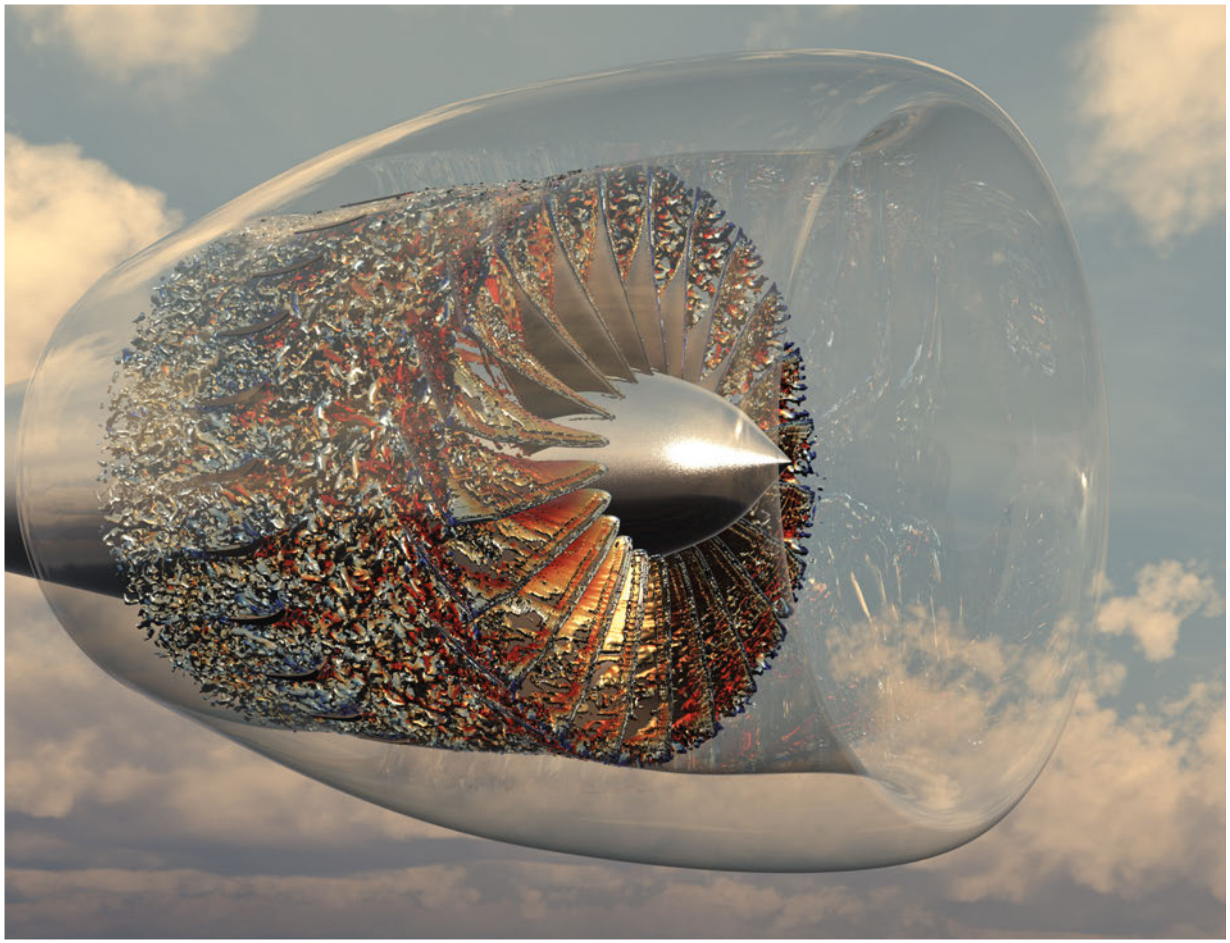




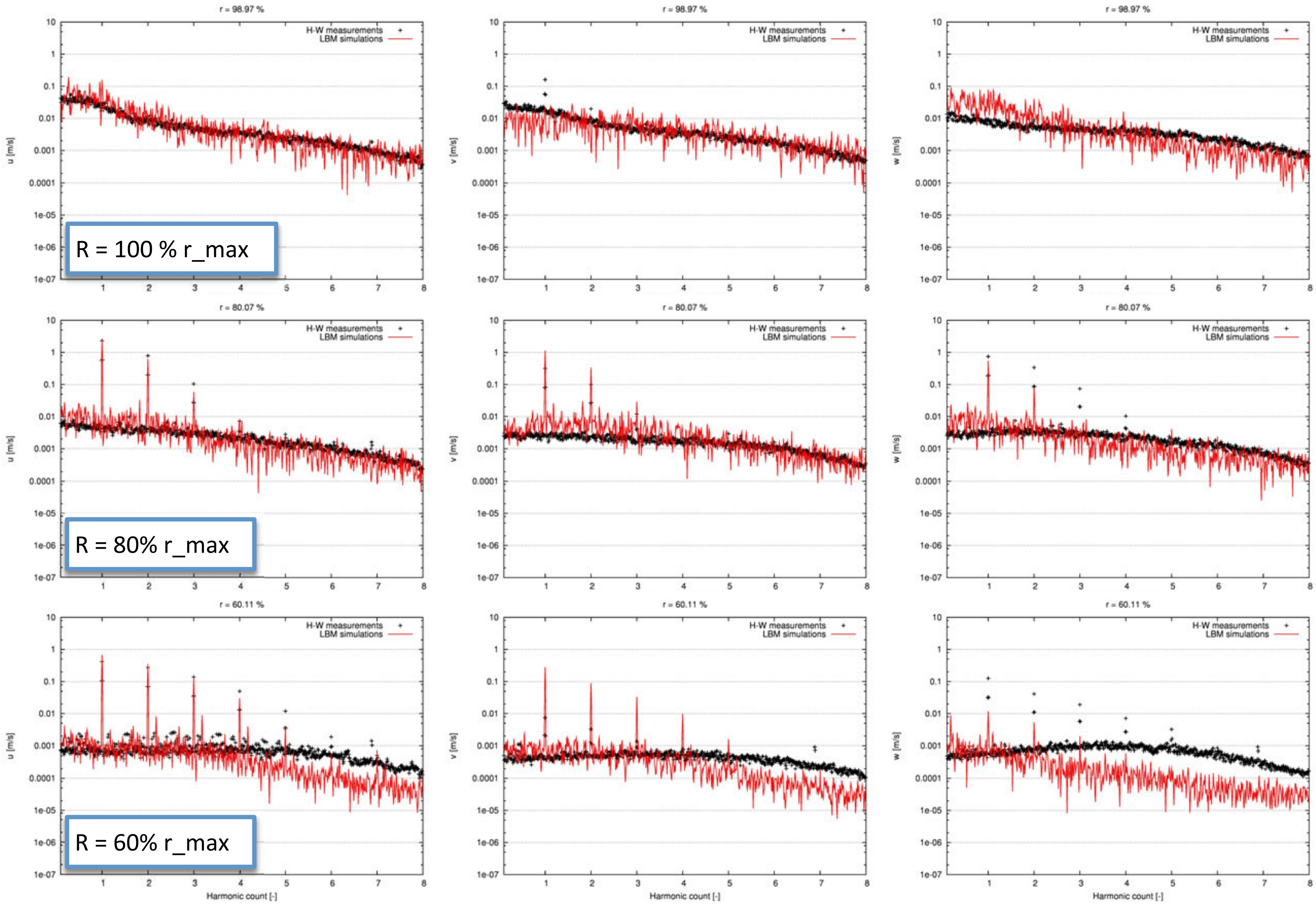
3D Ice Shape – Surface Flow Visualization



Fan Noise: RC2 Fan/OGV Configuration

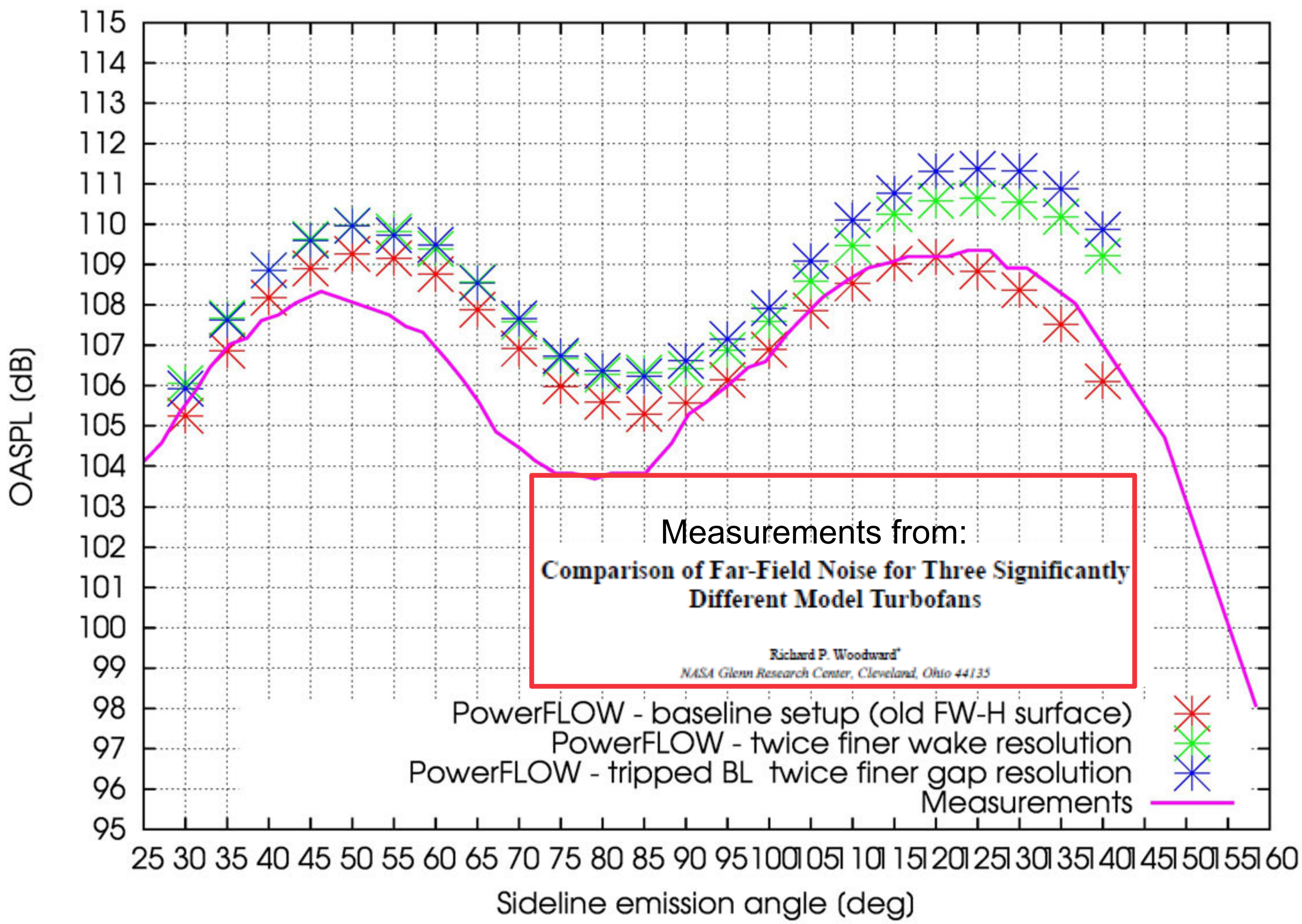


Flow results between rotor & stator – comparison with NASA measurements

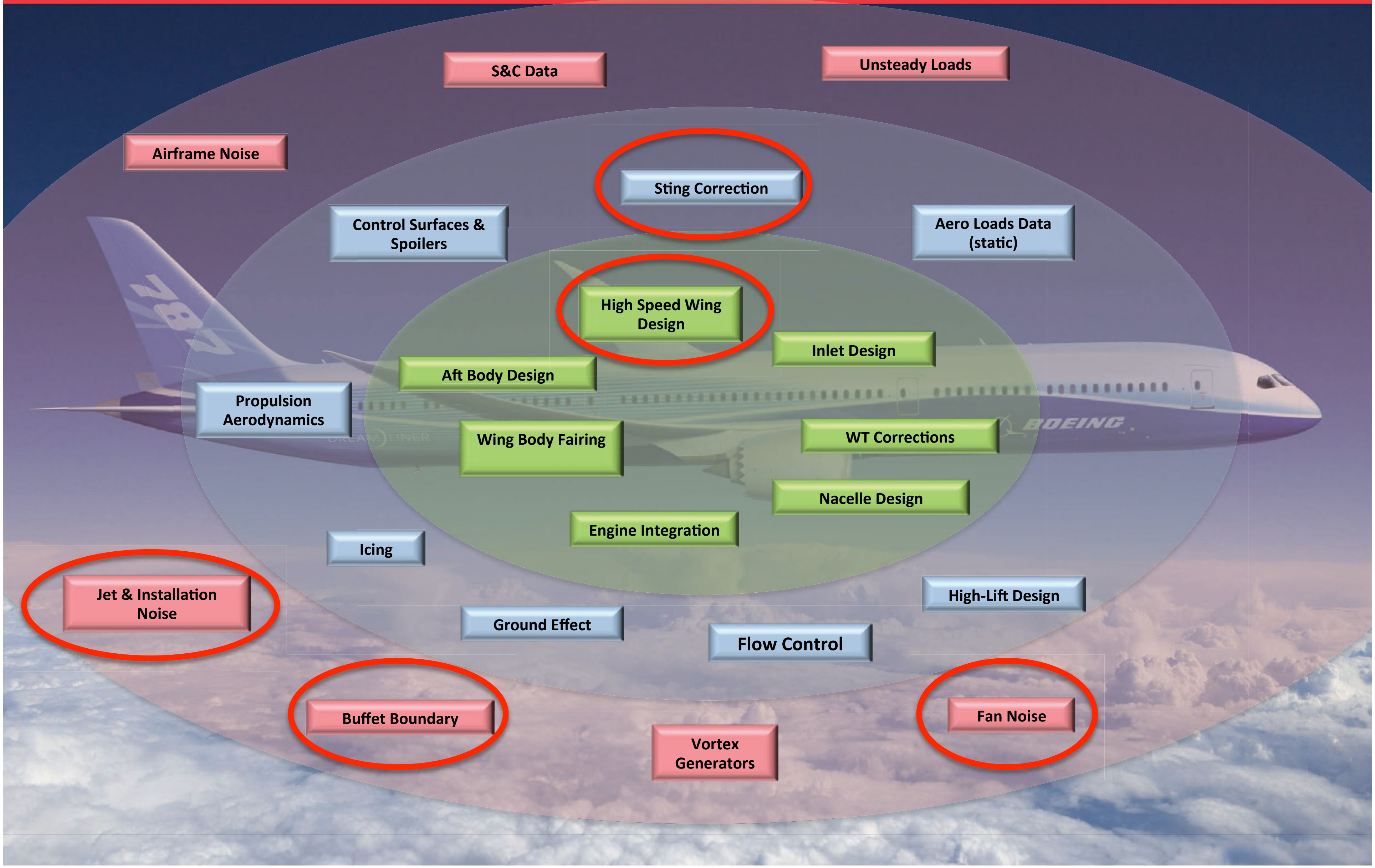


Velocity spectra
Tripped

Far-field noise results



High Speed Applications



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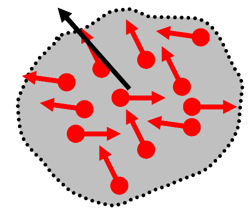
Kinetic theory: Basics

Boltzmann kinetic theory describes fluid behaviour based on particle density distribution function

$$f(\vec{x},\vec{c},t)$$

particle number density at time t and position x with velocity ***c***



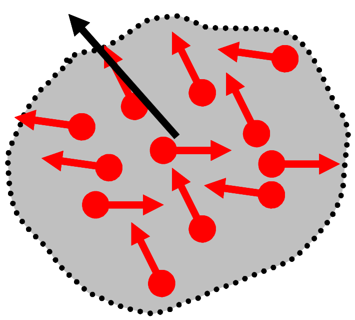
Boltzmann Equation:

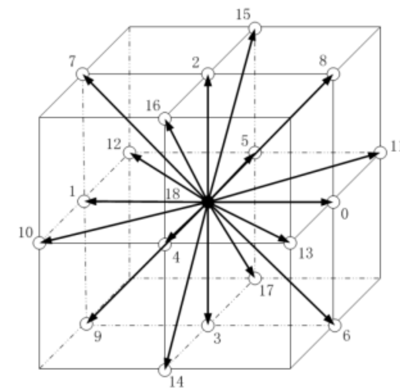
$$\frac{\partial}{\partial t} f(\vec{x},\vec{c},t) + \vec{c}\cdot\nabla f(\vec{x},\vec{c},t) = \Omega$$

- LHS represents advections of particle distribution in space at fixed velocity for each ***c***
- RHS defined the collision process that involves inter-particle interactions
- Collision process can be modeled as simple relaxation to its equilibrium state (e.g. the BGK form*)

Lattice Boltzmann Methods

Discretization in space and time, using a finite set of discrete particle velocity values to represents the hydrodynamic properties*:





D3Q19 lattice

Lattice Boltzmann Equation :

$$f_i(\vec{x}+\vec{c}_i, t+1) - f_i(\vec{x}, t) = \Omega_i(\vec{x}, t)$$

BGK form of collision:

$$\Omega_i(\vec{x}, t) = -\frac{1}{\tau}\left[f_i(\vec{x}, t) - f_i^{eq}(\vec{x}, t)\right]$$

Lower order LBE model recovers the Navier-Stokes equation at the nearly incompressible limit**

**Chen & Doolen 1998 **Qian et al. 1992., Chen et al 92*

Lattice Boltzmann Methods

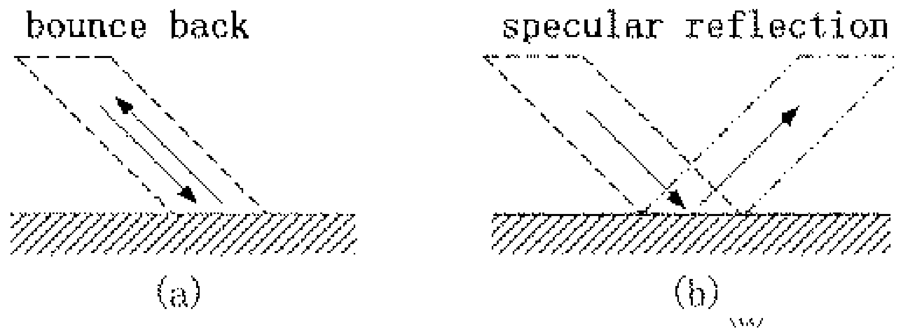
- Macroscopic quantities are direct results of the moments of particle density distributions
  - *Density* $\rho(\vec{x},t) = \sum_i f_i(\vec{x},t)$
  - *Velocity* $\rho(\vec{x},t)\vec{u}(\vec{x},t) = \sum_i \vec{c}_i f_i(\vec{x},t)$
  - …

- Pressure obeys the thermally perfect gas law

$$P = \rho\theta \qquad \theta = RT$$

LBM Surface Dynamics

- No-slip/freeslip BCs are achieved via bounce-back/specular-reflection process*



- Momentum flux across the fluid-solid interface corresponds to surface pressure and wall shear stress*

$$\mathbf{F} = p\hat{n} + \tau_w \hat{t} \sim \sum_{m \in Pgrams,out} \left[\left(\vec{c}_m f_m \right)^{out} - \sum_{n \in Pgrams,in} \left(\vec{c}_n f_n \right)^{in} \right]$$

- Generalized slip algorithm has been formulated to realize turbulence wall boundary conditions (slip velocity with imposed wall frictions)

Remarks

- Properly constructed LBE models can recover N-S physics, … and beyond!
- LBM is a very accurate solver with extremely low numerical dissipation
  - *Convection is exact due to the limited discrete velocities*
- Very efficient for performing time dependent flow simulations
- A very robust solver due to realizability, and stability condition is *a priori* guaranteed

- Plus …. Special Features of LBM Implementation in PowerFLOW
  - *Near wall physics (surfel concept)*
  - *LBM-VLES turbulence model*
  - *Variable resolution*
  - *Efficient parallel implementation*
  - *Extension to supersonic speeds*

LBM-VLES Turbulence Model

- LBM-VLES turbulence model concept
  - *Single turbulence model for all flow conditions*
  - *Resolved turbulent structures are simulated directly, unresolved scales are modeled*
  - *Subgrid contributions are accounted for by an effective relaxation time scale*

$$f_i(\vec{x}+\vec{c}_i\Delta t, t+\Delta t) - f_i(\vec{x},t) = -\frac{1}{\tau}\left(f_i - f_i^{eq}\right) \quad \Rightarrow \quad F_i(\vec{x}+\vec{c}_i\Delta t, t+\Delta t) - F_i(\vec{x},t) = -\frac{1}{\tau_{effective}}\left(F_i - F_i^{eq}\right)$$

- Modification of turbulent flow relaxation time
  - *Derived from a systematic renormalization group (RNG) procedure*

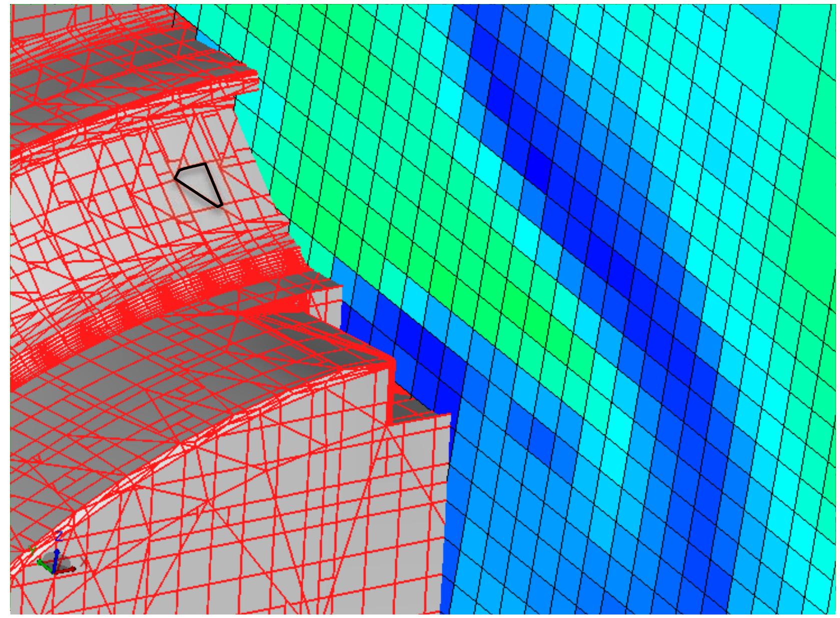
$$\tau_{effective} = \tau_0 + \tau_{turb}, \qquad \tau_{turb} = C_\mu \frac{k^2}{\varepsilon} \frac{1}{T\sqrt{1+\tilde{\eta}^2}}, \qquad \tilde{\eta} = \psi\left(\eta_s, \eta_\Omega, \eta_h \ldots.\right)$$

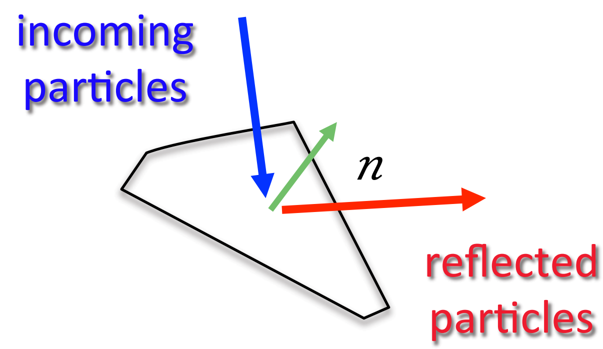
  - *where* $\tilde{\eta}$ *is the time scale of mean flow (strain, swirl, buoyancy, ….)*
  - *Effectively reduces eddy-viscosity in regions of high vortical fluctuations (e.g. separated regions)*
  - *Conceptually similar to DDES & SAS*
- LBM-VLES contains HOT to account for non-linearity of the Reynolds stress

Chen, H., et al. "Expanded analogy between Boltzmann kinetic theory of fluids and turbulence.“, JFM, 2004.

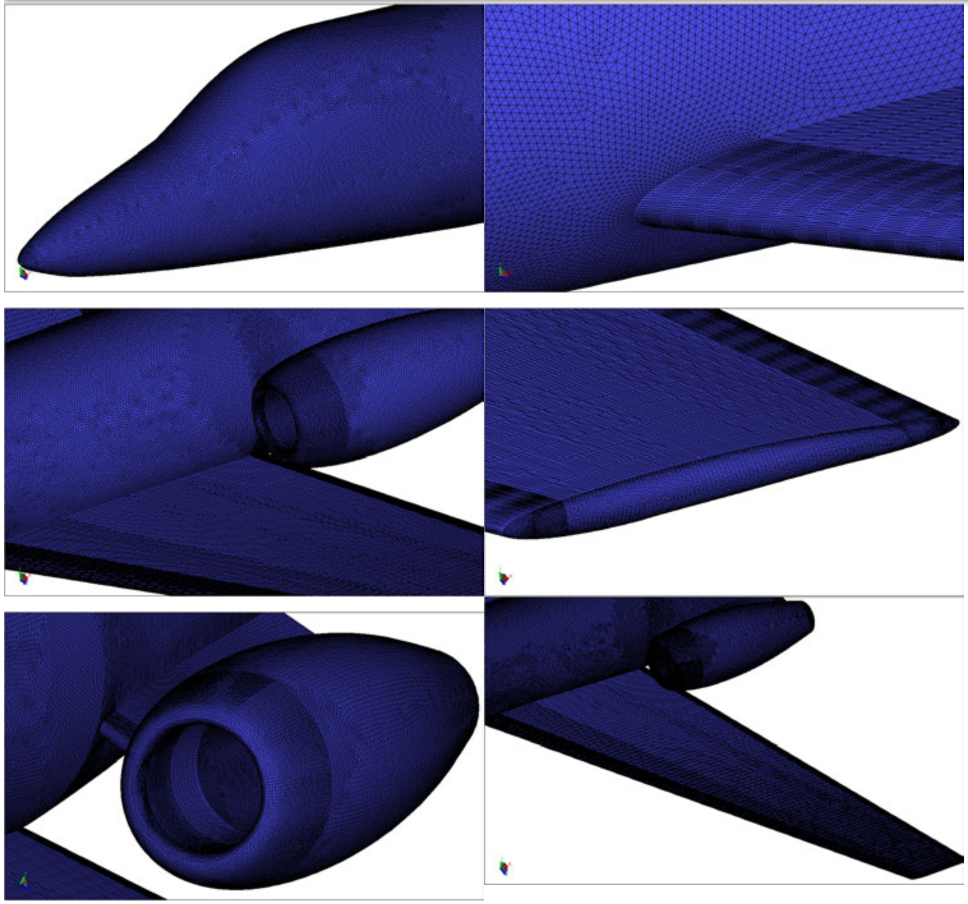
Near Wall Physics in PowerFLOW

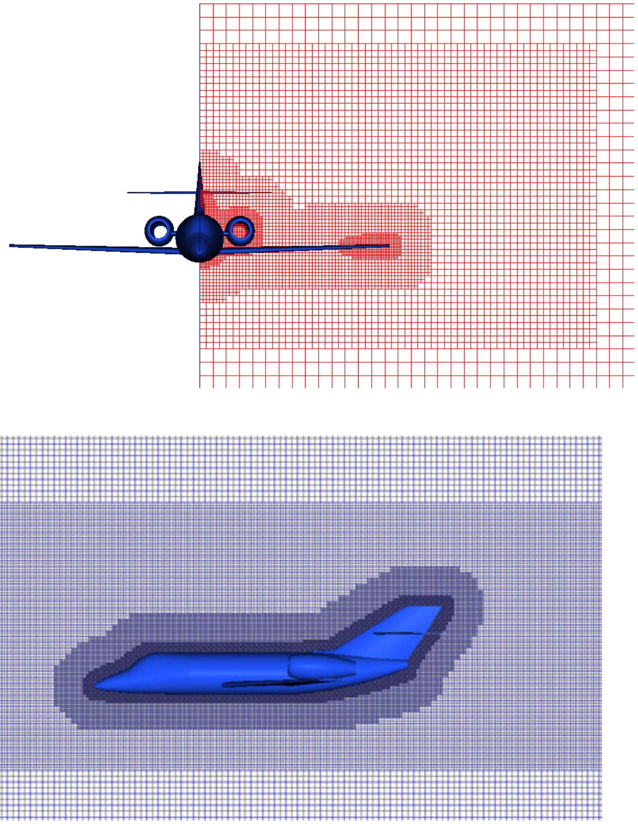
- **Surfel Concept**
  - *Arbitrary orientation & shape of elements*
  - *Near wall Sampling*
    - All needed weights pre-computed based on near wall volume elements
    - Ensure Conservation
  - *Momentum exchange*
    - Correspond to changes in pressure and friction
  - *Second Order Accuracy*
  - *Extended wall model for high Re#*
    - Including pressure gradient effects





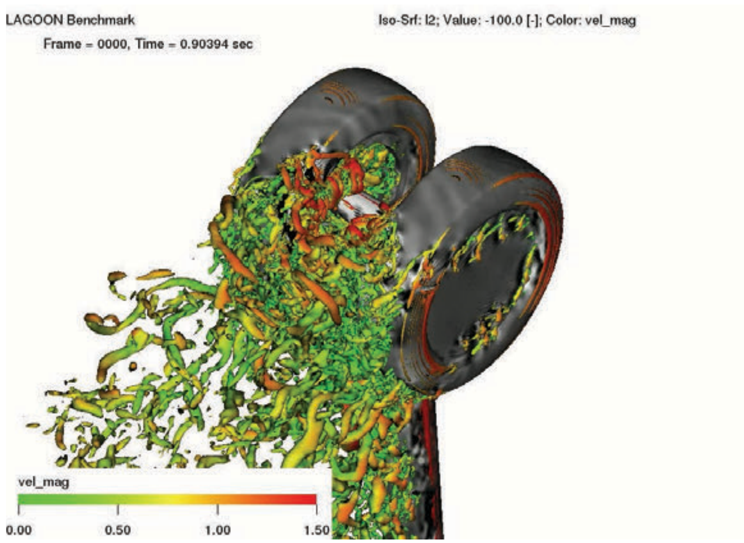
Typical Cartesian Grids Generation





Once surface grids and regions of refinement are defined, volume grid generation is fully automatic

Efficient Parallel Implementation

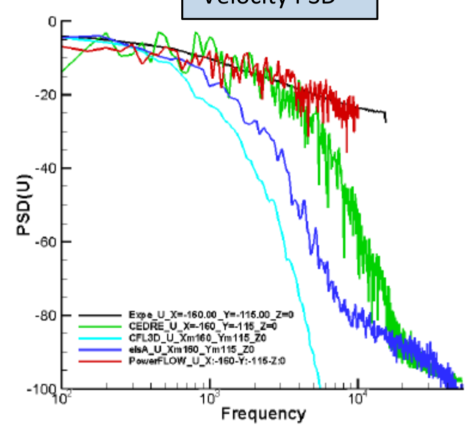


	Power-FLOW	CFL3D	CEDRE
Turb. Model	VLES	MDDES	ZDES
Number of Elements	123M	43M	61M
Number of Procs.	276	240	480
CPU-hrs for 1s simulated time*	21,000	854,000	1,960,000

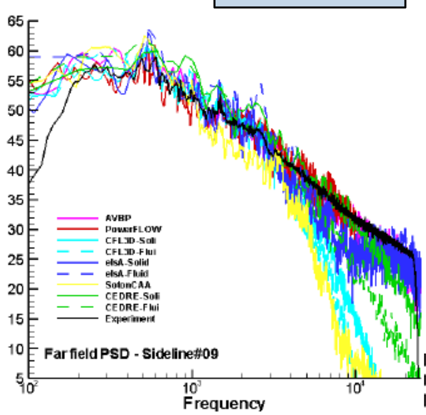
* Manoha (Onera), Caruelle (Airbus), AIAA-2015

Lagoon (BANC-III

Velocity PSD



Farfield PSD



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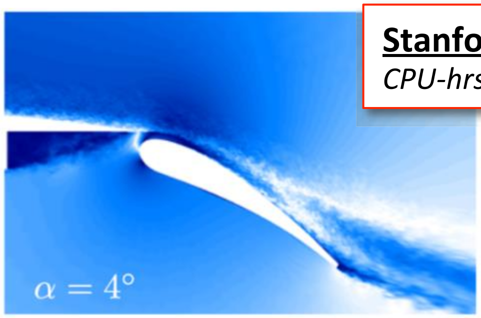
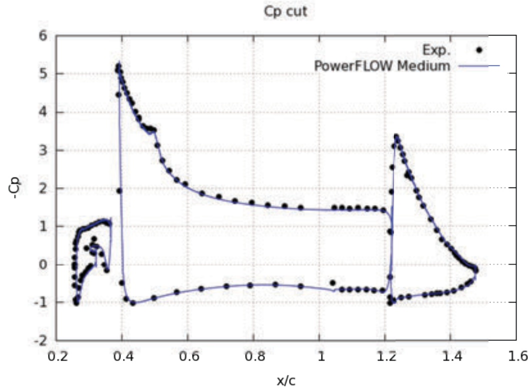
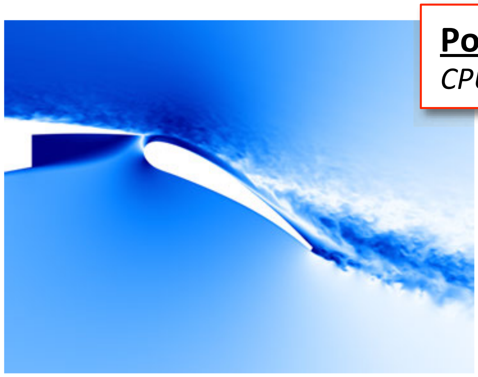


Stanford WMLES*
*CPU-hrs: 17,000,000***





PowerFLOW***
*CPU-hrs: 5,000***

* Bodart, Larson, Moin, "Large eddy simulation of high-lift devices", AIAA 2013-2724.

** CPUh normalized for 1 flow pass and a span of 1 chord

*** Simulations executed in collaboration with NASA

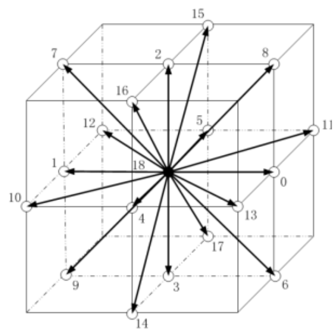
Exa

Extension of LBM to Transonic/High speed Flows

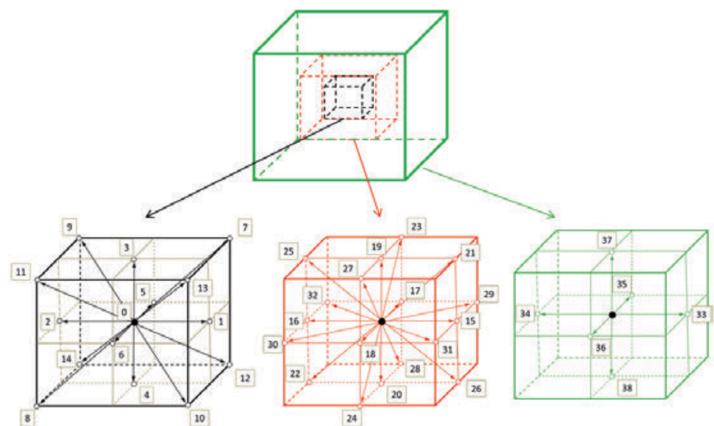
- Rigorous Theory based on Hermite Expansions (Shan et al, 1998, 2006)
  - *Projection of LBM in Hermite Polynomials*
    - Expansion coefficients are the moments of distribution function
    - No assumption on small Ma# or constant Temperature
  - *Truncate the expansion to certain order*
  - *Represent solution in Velocity Space*

Extension of LBM to Transonic/High speed Flows

- High order multi-speed LBE models (D3Q27, D3Q39, D3Q125 …)



D3Q19 Model
Ma_∞~0.4 (Ma_{local}~0.99)



Hybrid D3Q39 Model Ma_{max}~2.0

- Hybrid approach to couple with thermal dynamics field

$$\partial_t S + u_\alpha \partial_\alpha S = -\frac{1}{\rho\theta}\partial_\alpha q_\alpha + \frac{\Phi}{\rho\theta}. \qquad S = c_v ln\left(\frac{\theta}{\rho^{\gamma-1}}\right)$$

Nie, X.B., Shan, X., and Chen, H., "Lattice-Boltzmann/Finite-Difference Hybrid Simulation of Transonic Flow", AIAA-Paper 2009-139

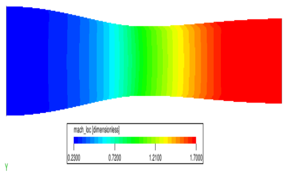
Exa

Outline

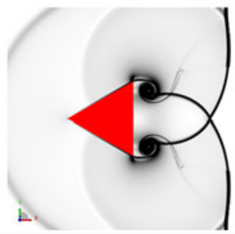
- Motivation: CFD Applications in Aerospace
- Overview of PowerFLOW Projects at NASA
- Theory & Background
  - *LBM*
  - *Turbulence model*
  - *Wall treatment*
  - *Extension to transonic flows*
- Transonic Code Validation and Application Examples
  - *Fundamental Validations*
  - *Industrial Application Examples*

Transonic Code Validation & Application

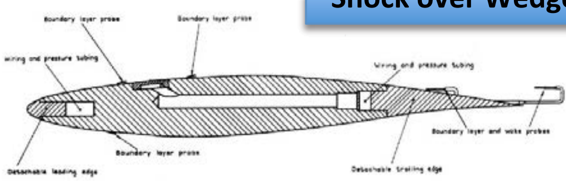
Fundamental Validations



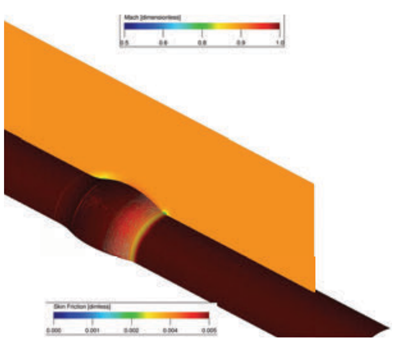
CDV nozzle



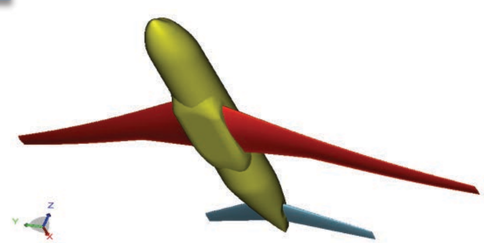
Shock over Wedge



RAE 2822 Airfoil

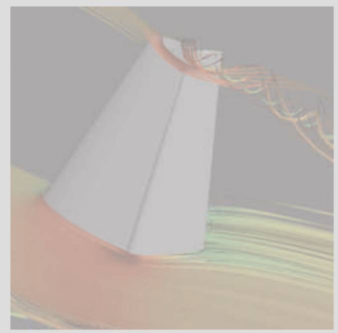


Transonic Bump

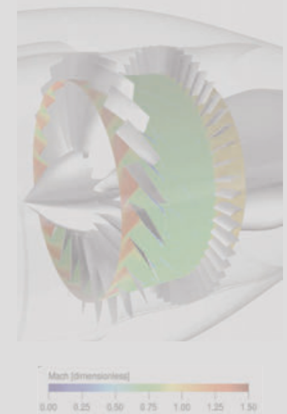


CRM

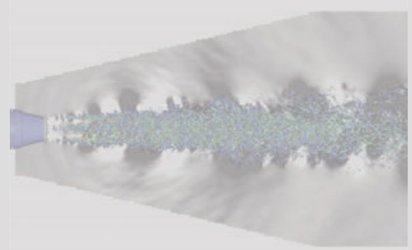
Industrial Applications



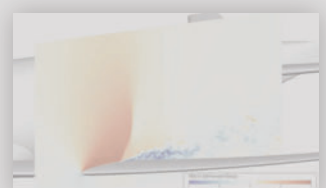
Flow Control



Fan Noise



Jet Noise

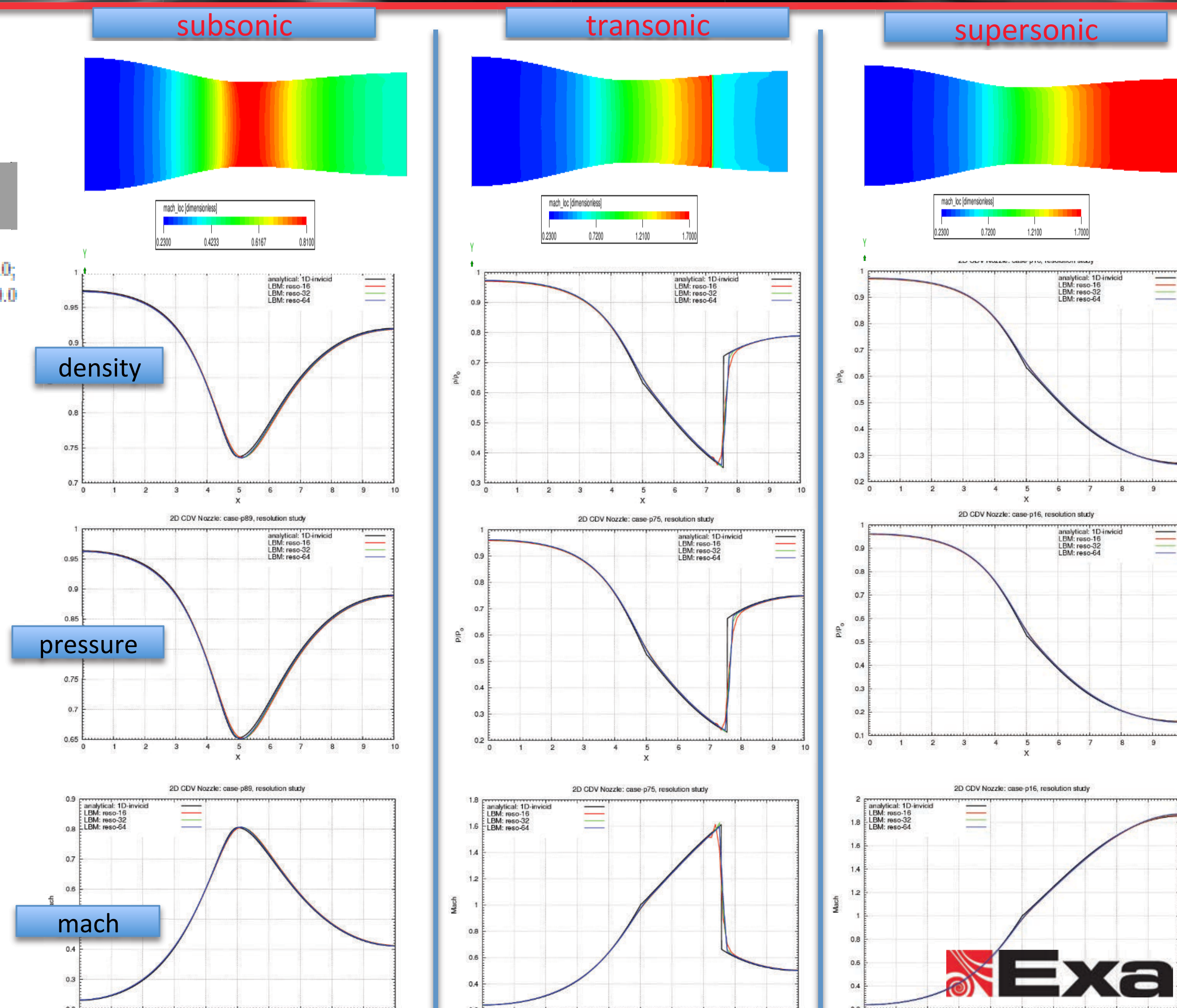


Buffet

2D CDV Nozzle (DNS): Sub-sonic/Transonic/Sueprsonic Flow Conditions

$$y(x)=\begin{cases} \pm|1.75-0.75\cos((0.2x-1.0)\pi)|, & \text{if } x \le 0.0; \\ \pm|1.25-0.25\cos((0.2x-1.0)\pi)|, & \text{if } x > 0.0 \end{cases}$$

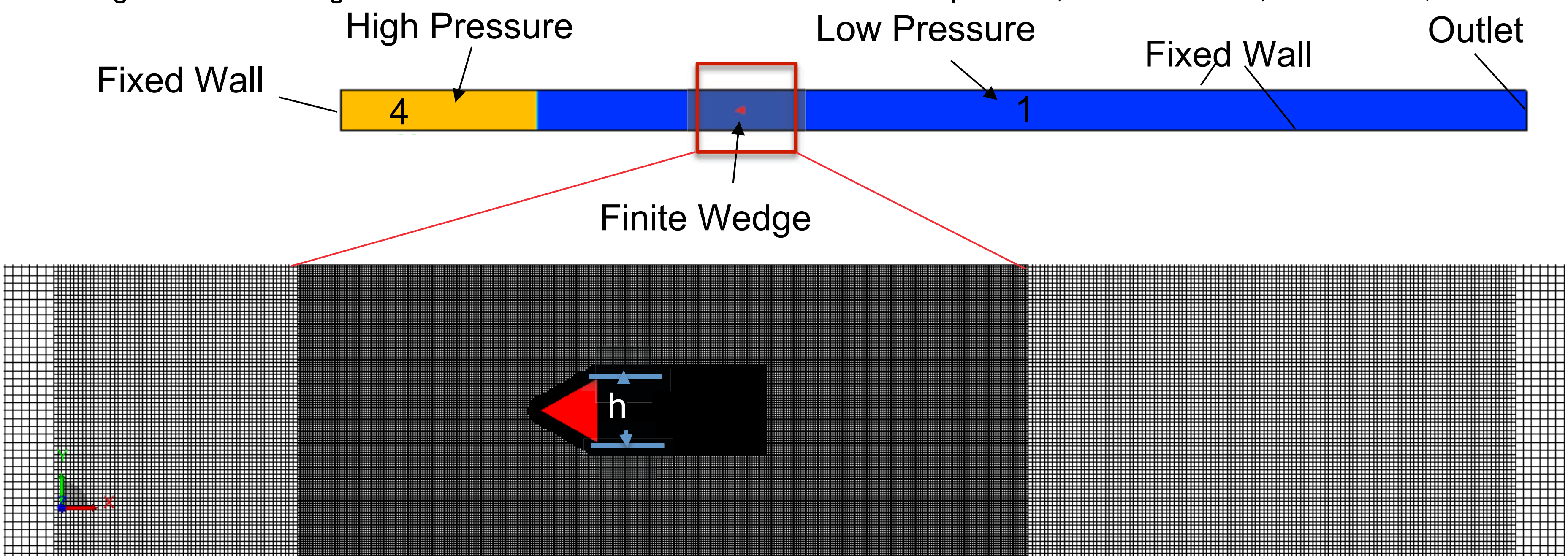
- Converge-Diverge Nozzle configuration
- Compared with analytical 1D invicid flow solution
- Simulated at low viscosity at various flow conditions



Collision of a Planar Shock with a Finite Wedge Setup

Shock Tube Setup

S-M. Chang and K-S. Chang: On the shock-vortex interaction in Schardin's problem, Shock Waves, 10:333-343, 2000



Initial Conditions:

P4/P1 = 4.0, T4/T1 = 1

Boundary Conditions:

No-slip walls
Outlet pressure P1
Re 50000

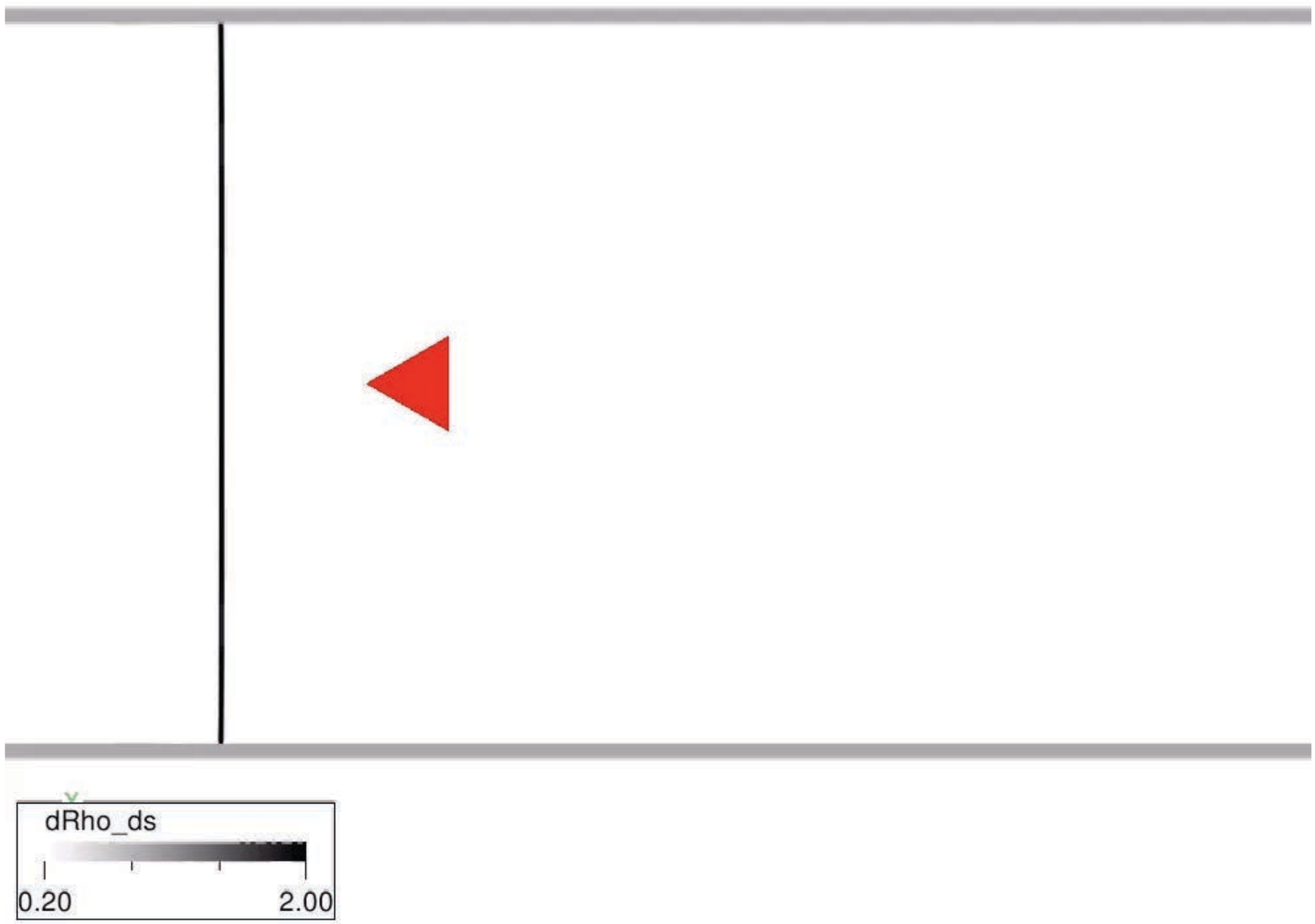
Grid Resolutions:

Coarse	h/128
Medium	h/256
Fine	h/512

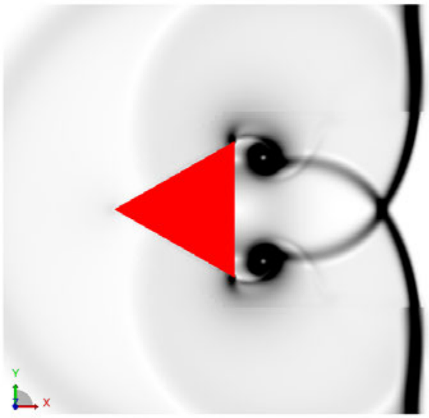
Collision of a Planar Shock with a Finite Wedge

Animation of the plane shock moving over the finite wedge (Animation time 0.001 s)

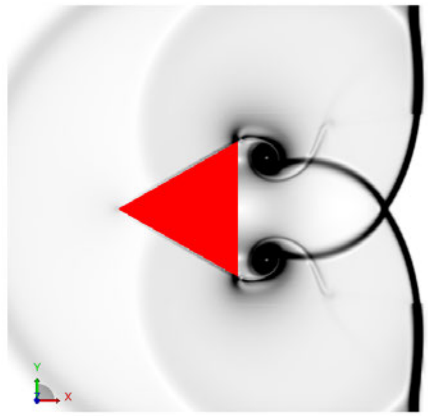
Planar shock moves
at Mach 1.34



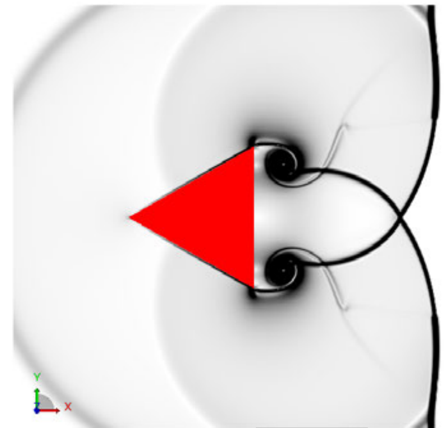
Collision of a Planar Shock with a Finite Wedge



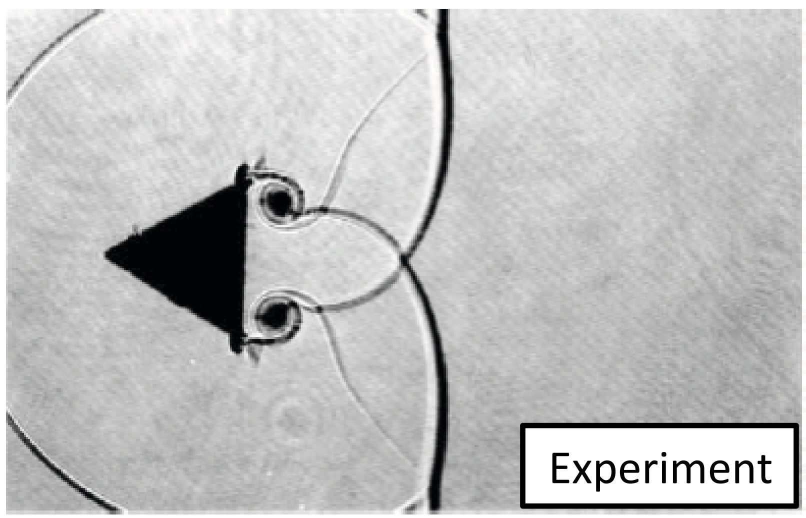
coarse



medium



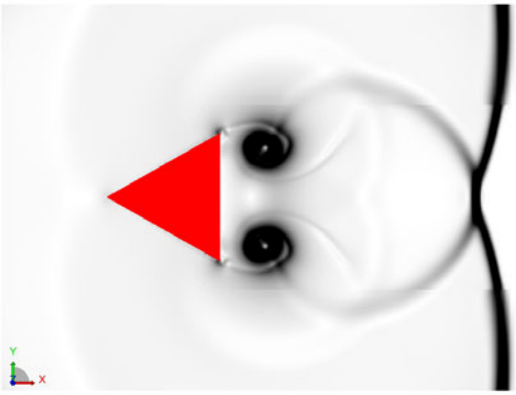
fine



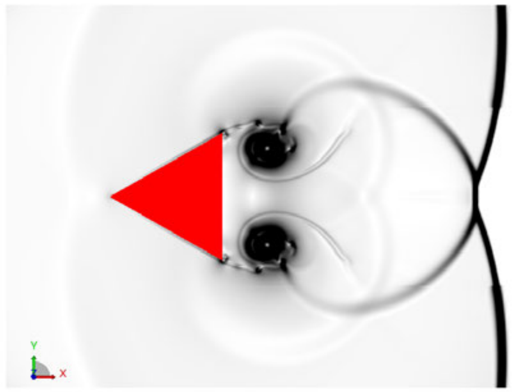
t = 91 μ sec

t = 0 corresponds to the instant, when the planar shock first collides with the finte wedge

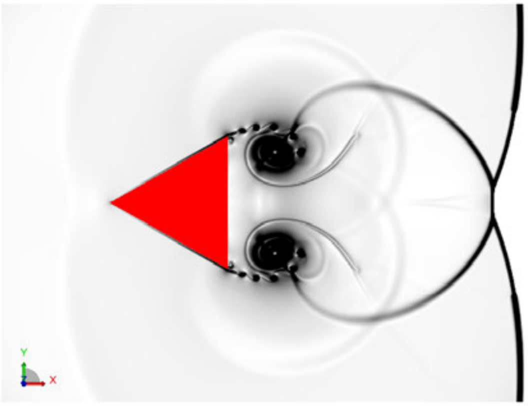
Collision of a Planar Shock with a Finite Wedge



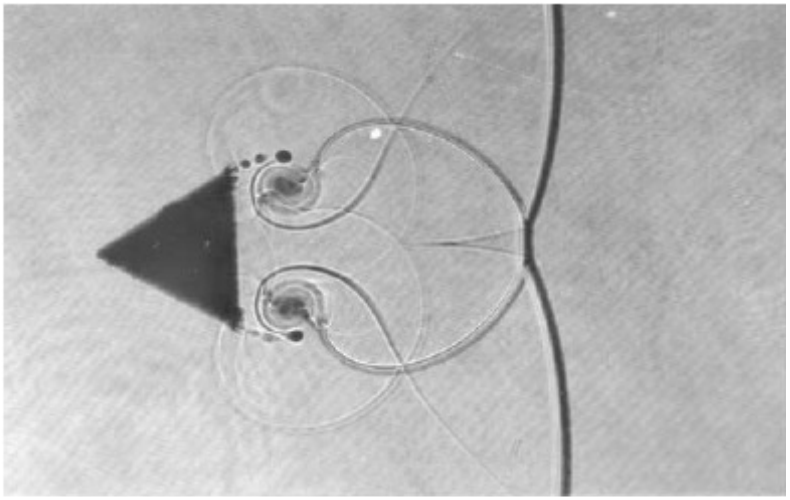
coarse



medium



fine

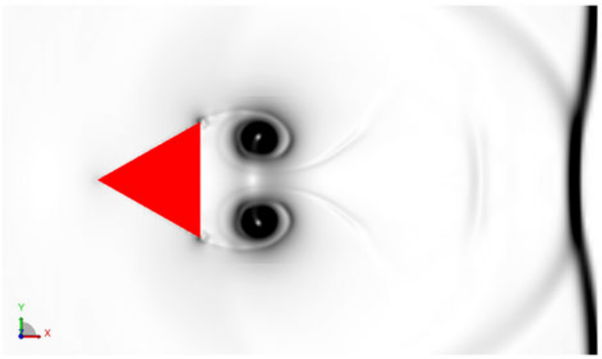


Experiment

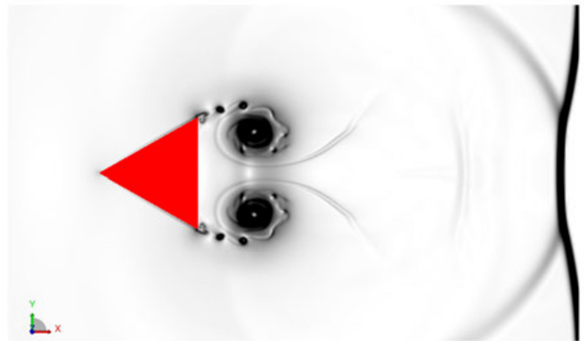
t = 128 μ sec

t = 0 corresponds to the instant, when the planar shock first collides with the finte wedge

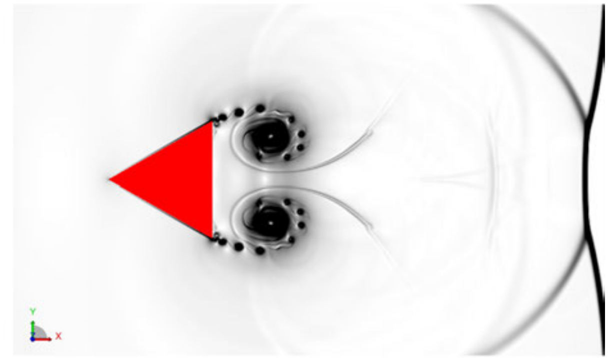
Collision of a Planar Shock with a Finite Wedge



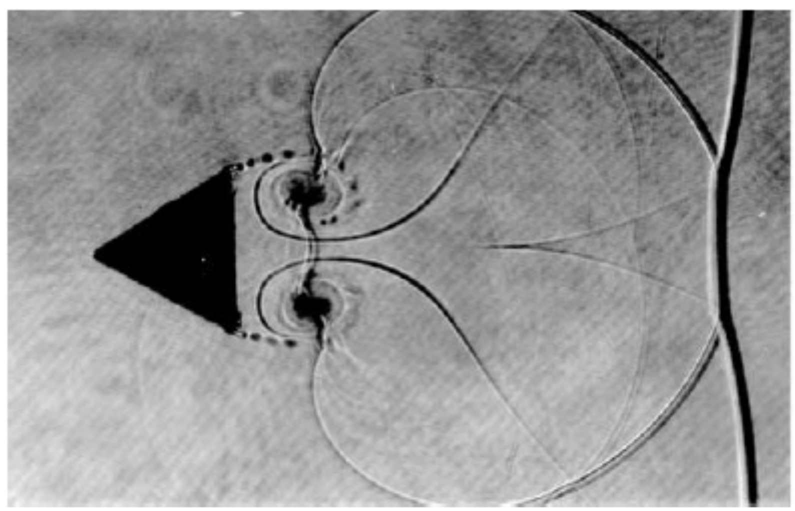
coarse



medium



fine



Experiment

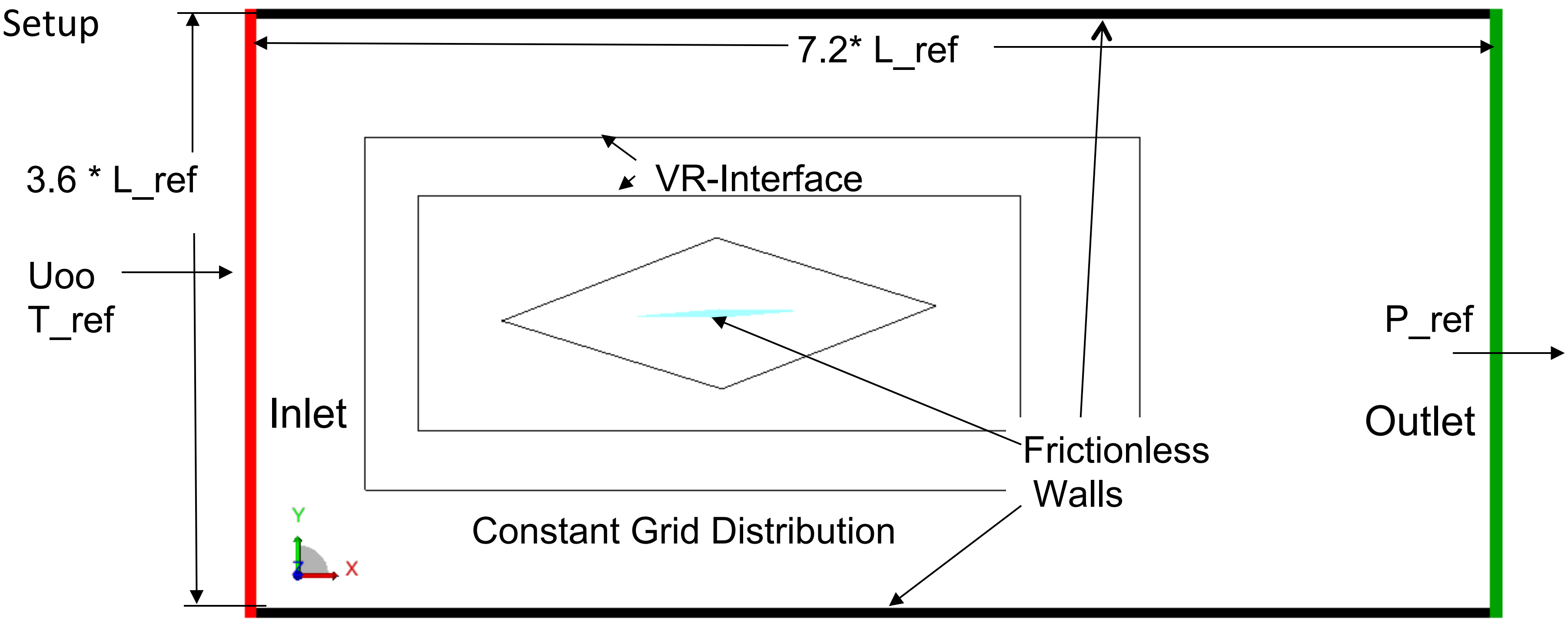
t = 151 μ sec

t = 0 corresponds to the instant, when the planar shock first collides with the finte wedge

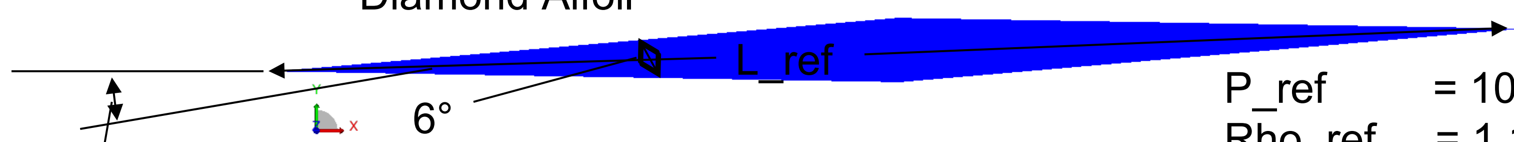
Exa

Supersonic Diamond Airfoil

Setup



Diamond Aifoil



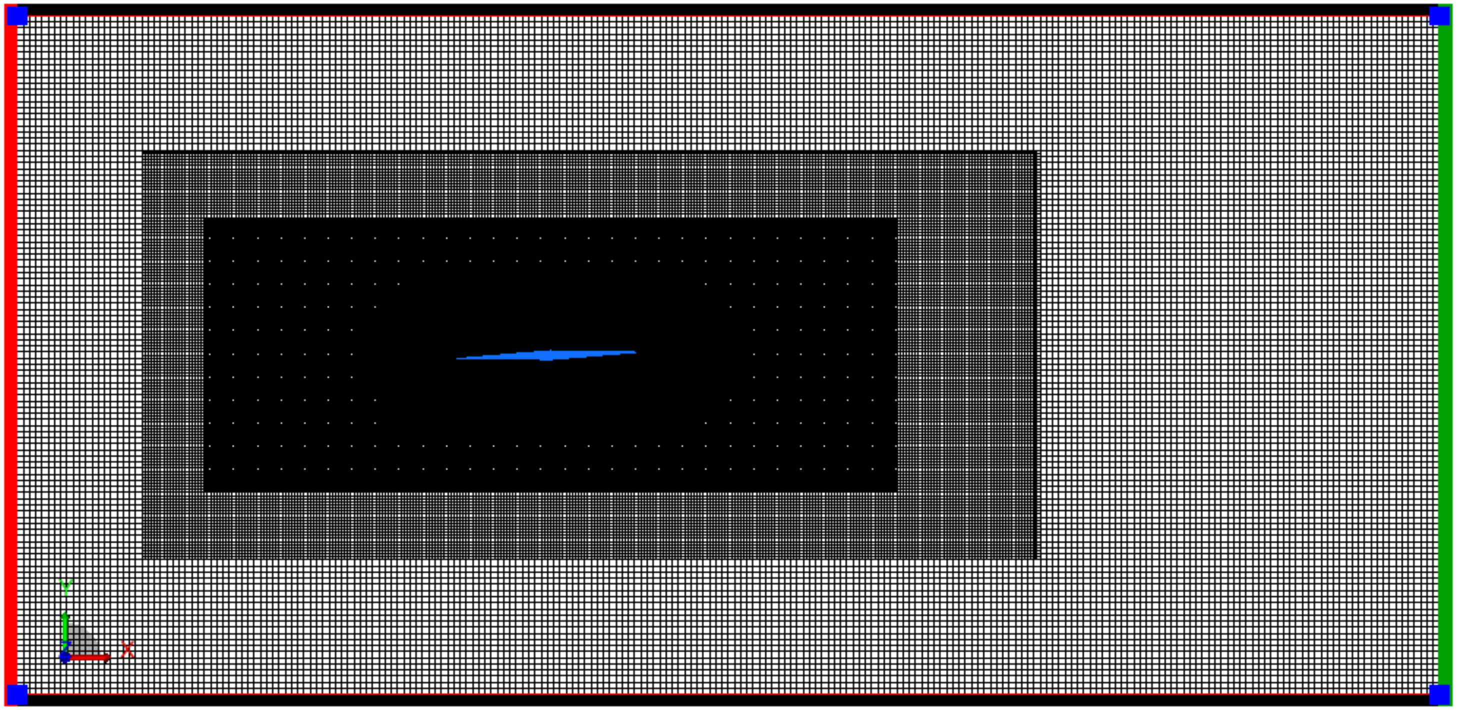
AOA (Angle of Attack)= -2°

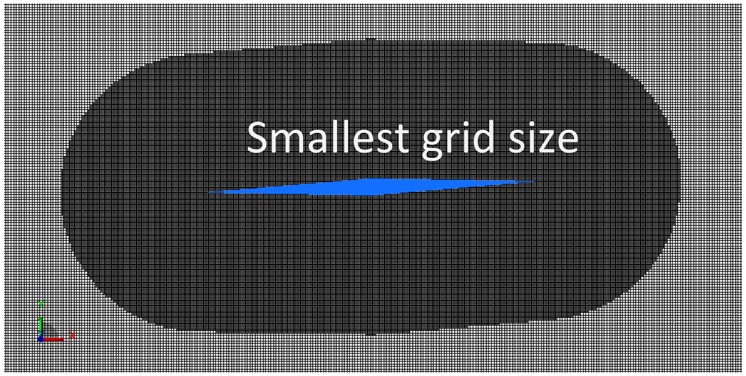
L_ref = 1 m
Area_ref = 1 m^2

2D-Turbulent-Simulation
Moo = 1.4
Re = 3.24E+07

P_ref = 100000 Pa
Rho_ref = 1.161 kg/m^3
T_ref = 300° K
AOA = -2°

Supersonic Diamond Airfoil

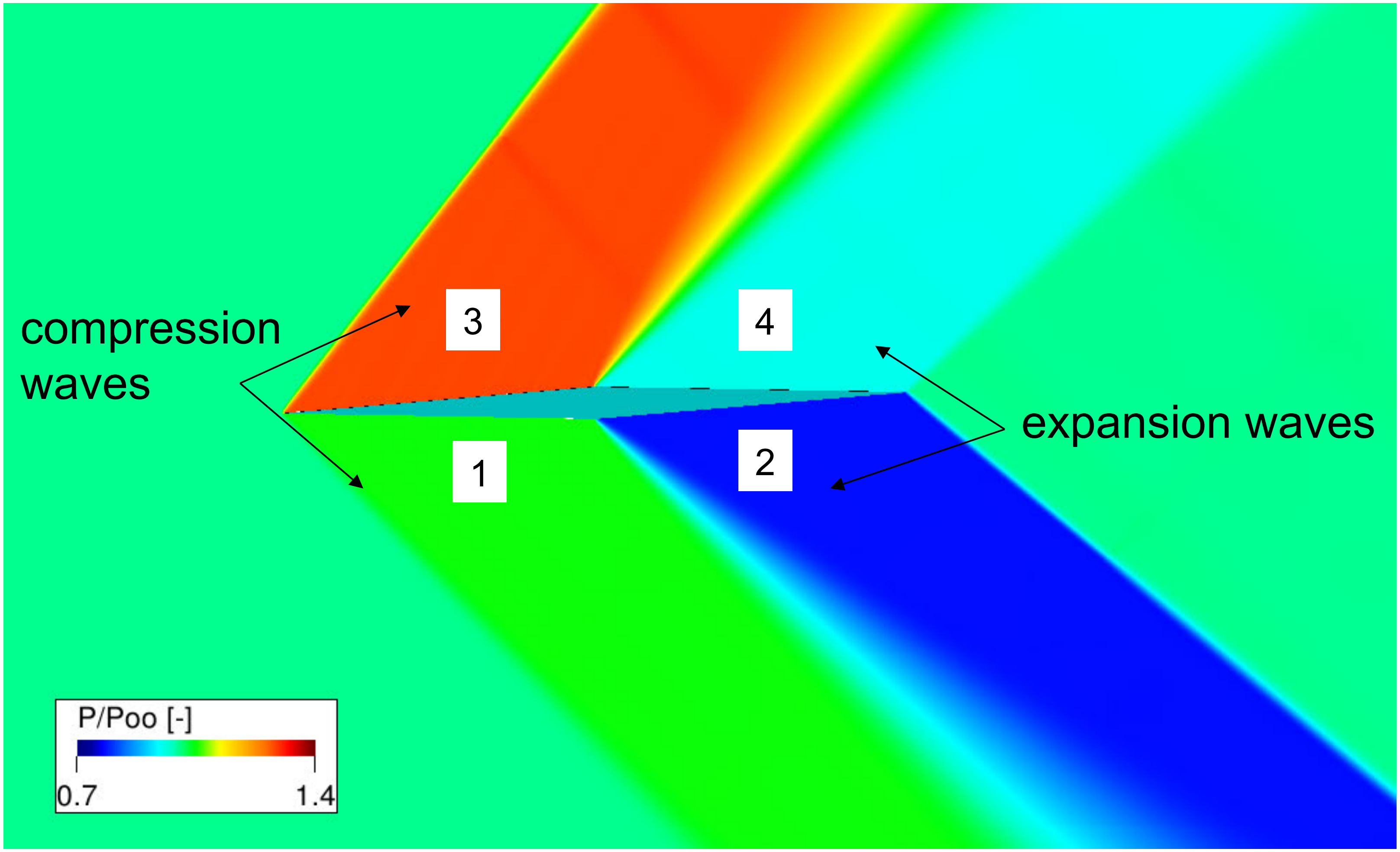




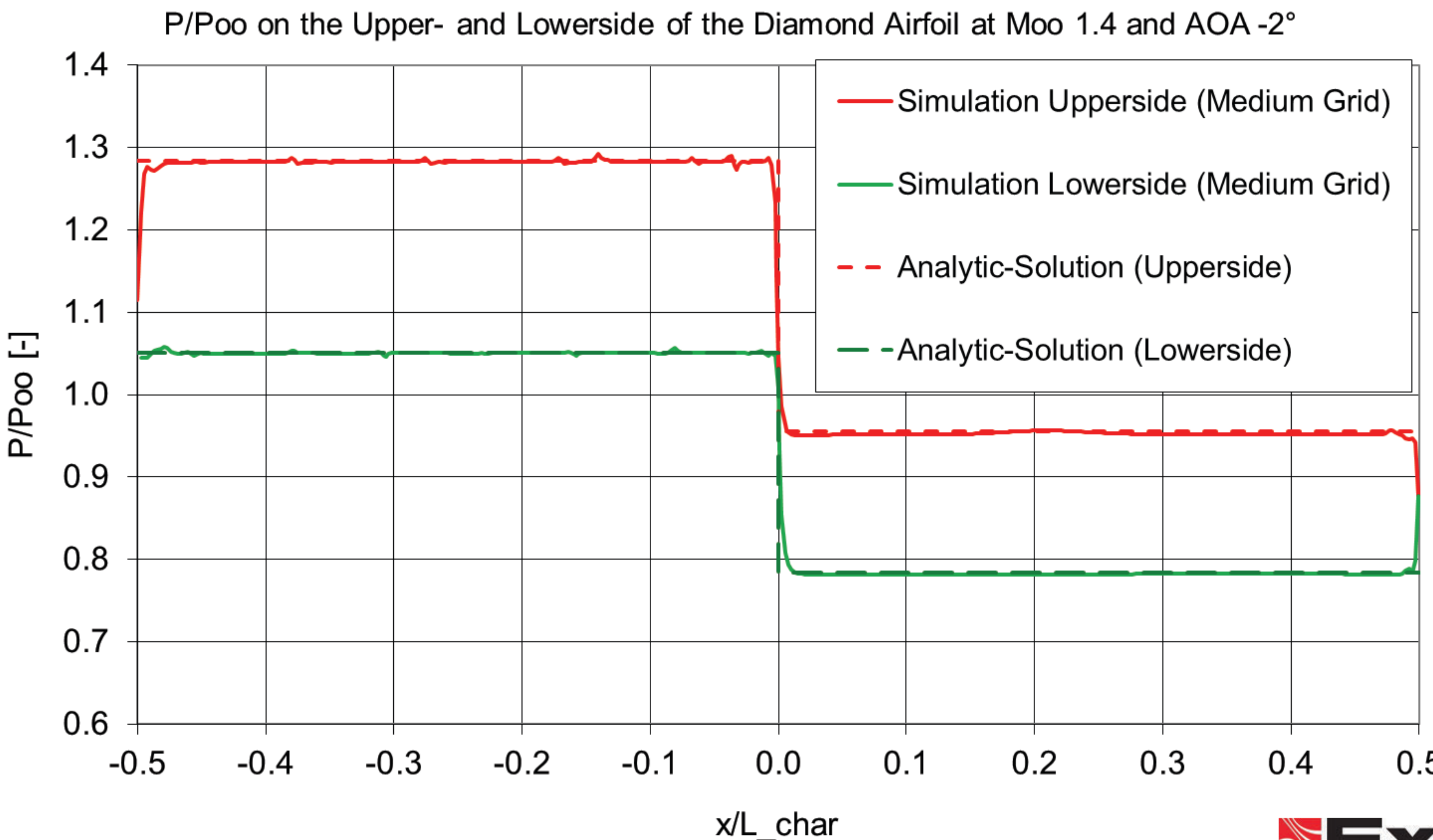
Grid
Resolution 512 per chord (coarse)
Voxel-Size 1000/512 = 1.95 mm
Total Voxels 1.46 Mill.
Fine Equivalent Voxels 1.01 Mill.

Supersonic Diamond Airfoil

Pressure Distribution for Moo 1.4 and AOA -2



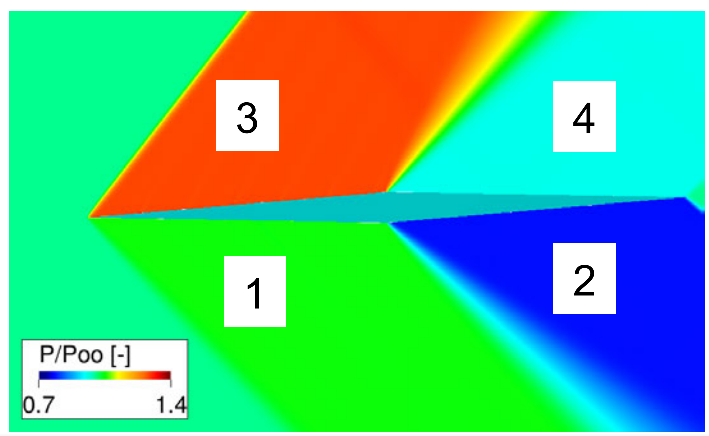
Supersonic Diamond Airfoil



Supersonic Diamond Airfoil

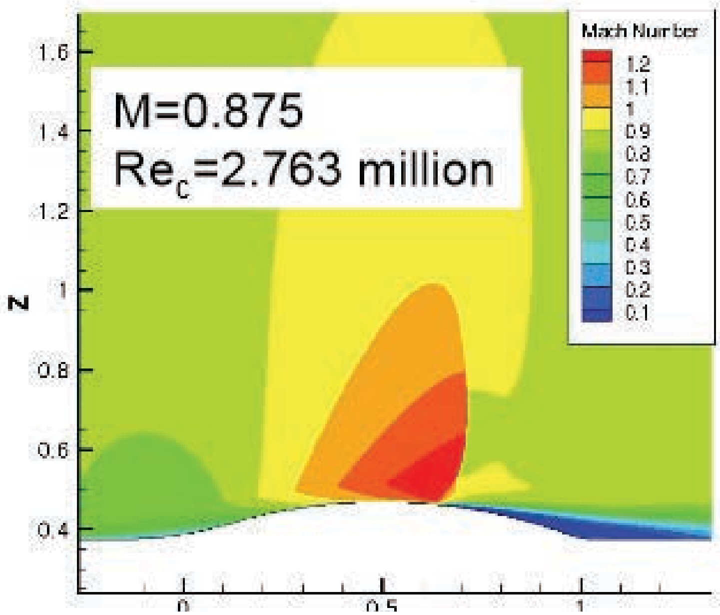
Angle of Attack AOA °	-2.0			
Inflow Mach Number Moo	1.4			
	Turbulent-Simulation			**Analytic-Solution**
Grid	**Coarse**	**Medium**	**Fine**	
Lift Cl [-]	0.1471	0.1474	0.1463	0.1473
Drag Cd [-]	0.0165	0.0165	0.0165	0.0165
Pressure Relation P1/Poo[-]	1.0502	1.0501	1.0502	1.0502
Pressure Relation P2/Poo[-]	0.7821	0.7819	0.7820	0.7838
Pressure Relation P3/Poo[-]	1.2823	1.2820	1.2821	1.2841
Pressure Relation P4/Poo[-]	0.9551	0.9555	0.9530	0.9553
Mach Number M1 [-]	1.3617	1.3637	1.3661	1.3650
Mach Number M2 [-]	1.5616	1.5625	1.5652	1.5690
Mach Number M3[-]	1.2109	1.2165	1.2215	1.2152
Mach Number M4 [-]	1.4241	1.4260	1.4267	1.4310

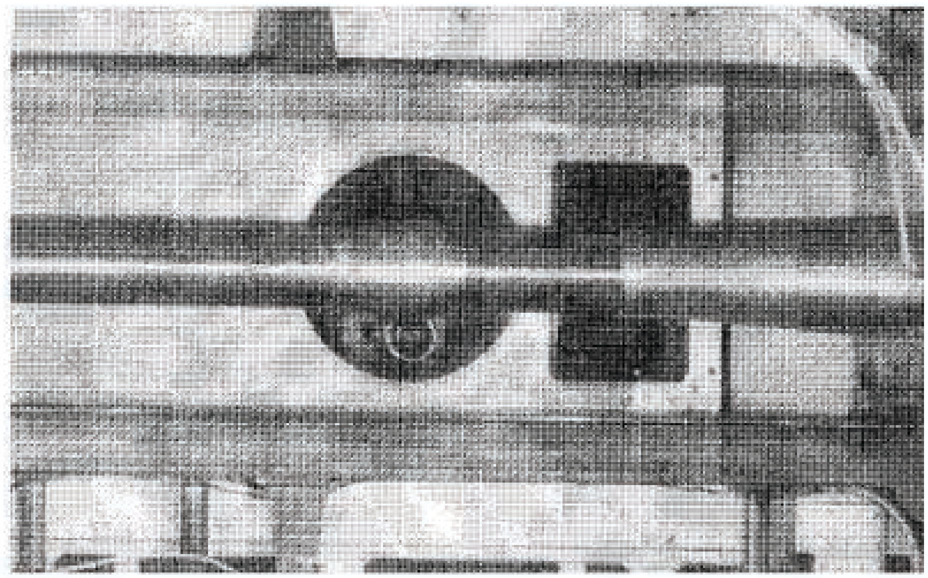
Resolution coarse = 512 per chord
Resolution medium = 768 per chord
Resolution fine = 1024 per chord



Axisymmetric Transonic Bump

- Part of NASA's 40% challenge
- Includes shock-induced separation, widely-used dataset for many years, axi-symmetry removes 2D questions
- RANS typically overestimates separation bubble by 20-30%

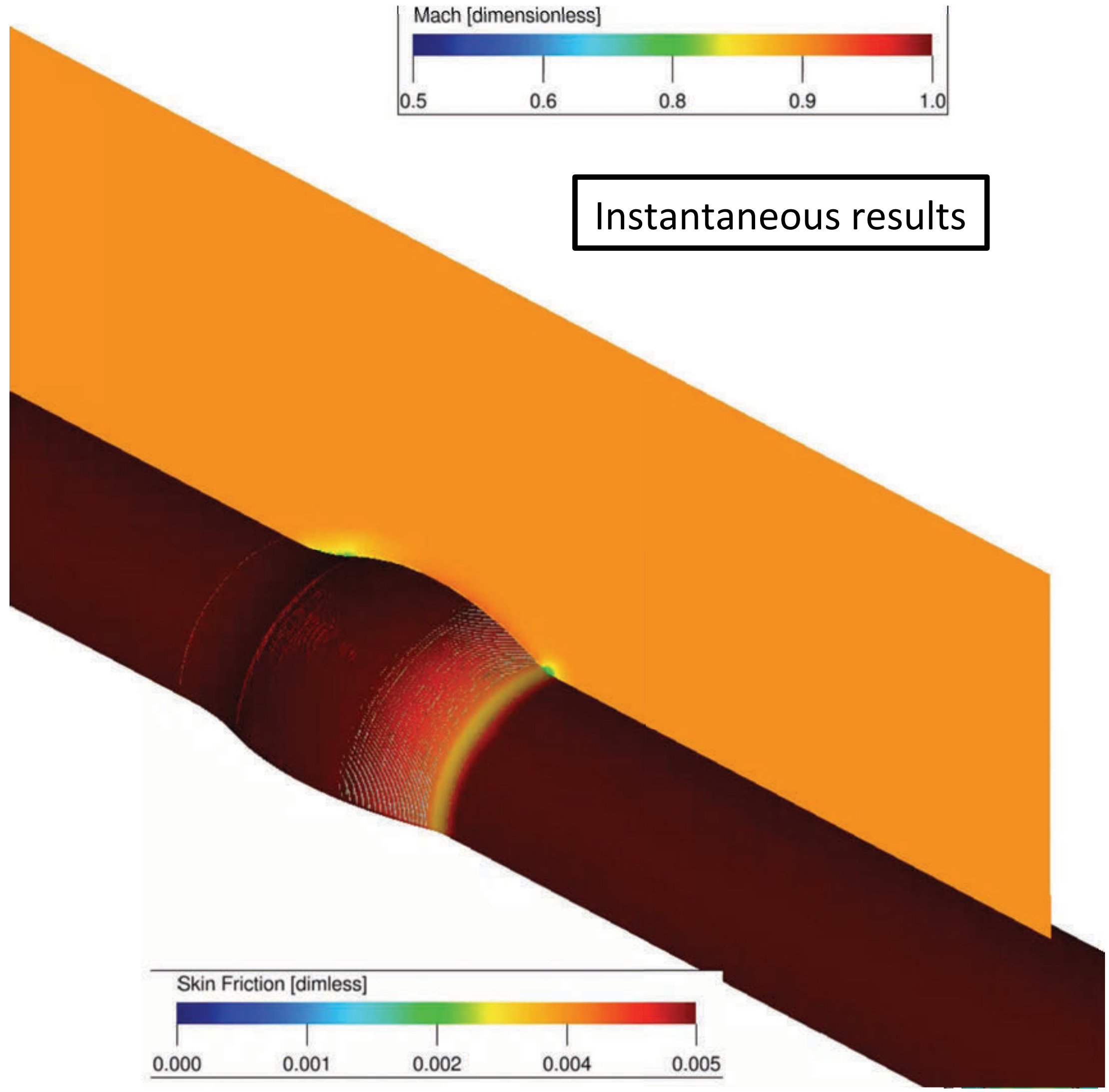




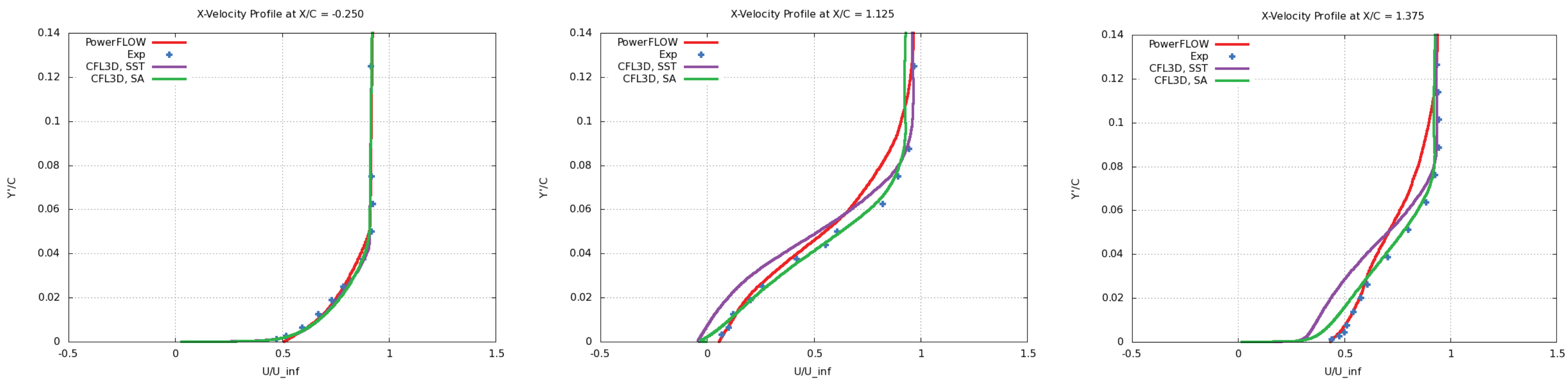
Bachalo, W. D., Johnson, D. A., "Transonic, Turbulent Boundary-Layer Separation Generated on an Axisymmetric Flow Model," AIAA Journal, vol. 24, no. 3, pp. 437-443, 1986.

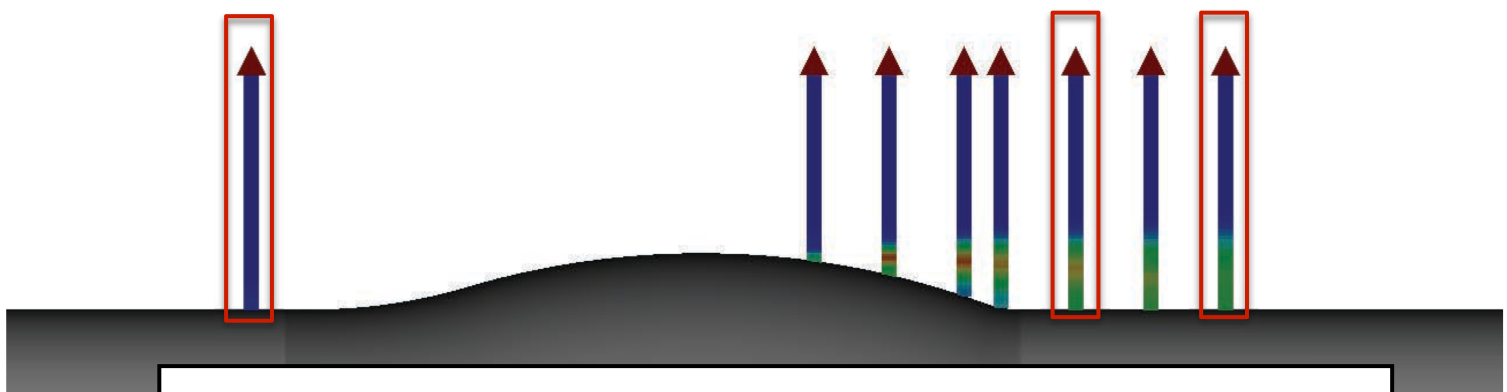
Axisymmetric Transonic Bump

- Volume cut shows location and sharpness of shock
- Skin friction contours indicate flow separation
- Iso-surfaces of λ_2 highlight resolved turbulent fluctuations in wake



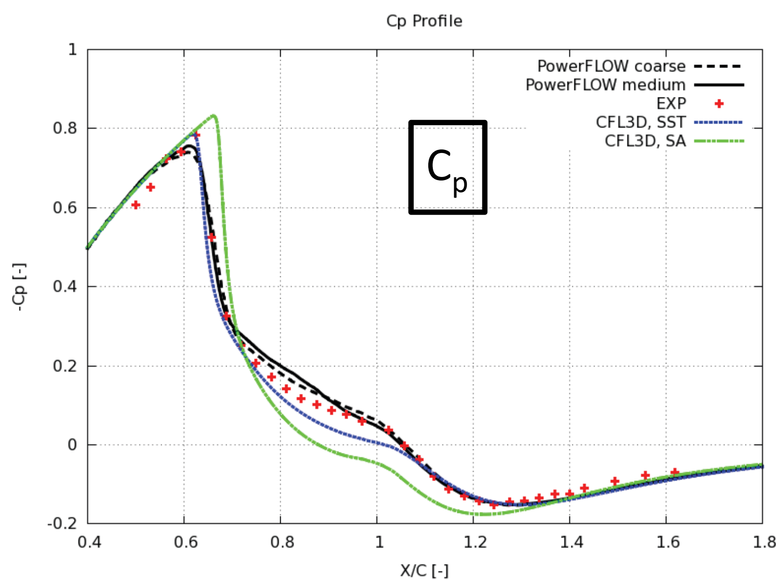
Axisymmetric Transonic Bump X-Velocity Profiles

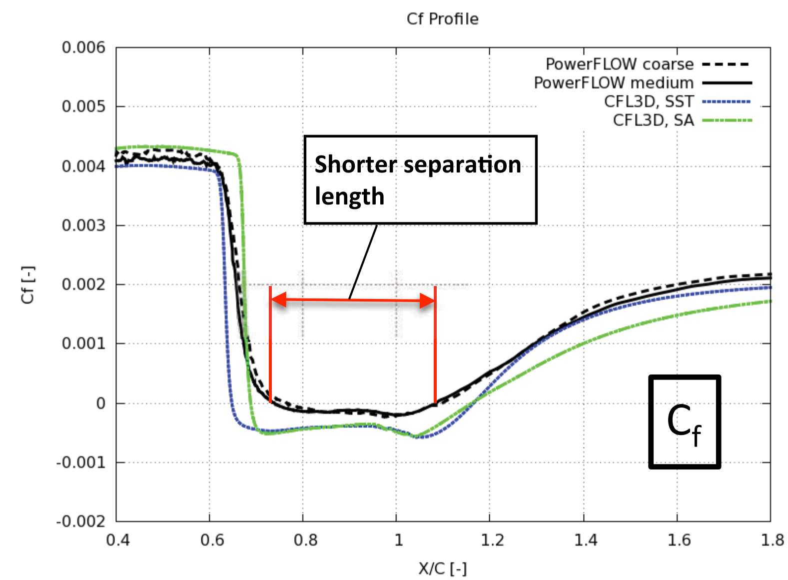




Reference Results from : Rumsey, C. L., "**Turbulence Modeling Resource,**" http://turbmodels.larc.nasa.gov

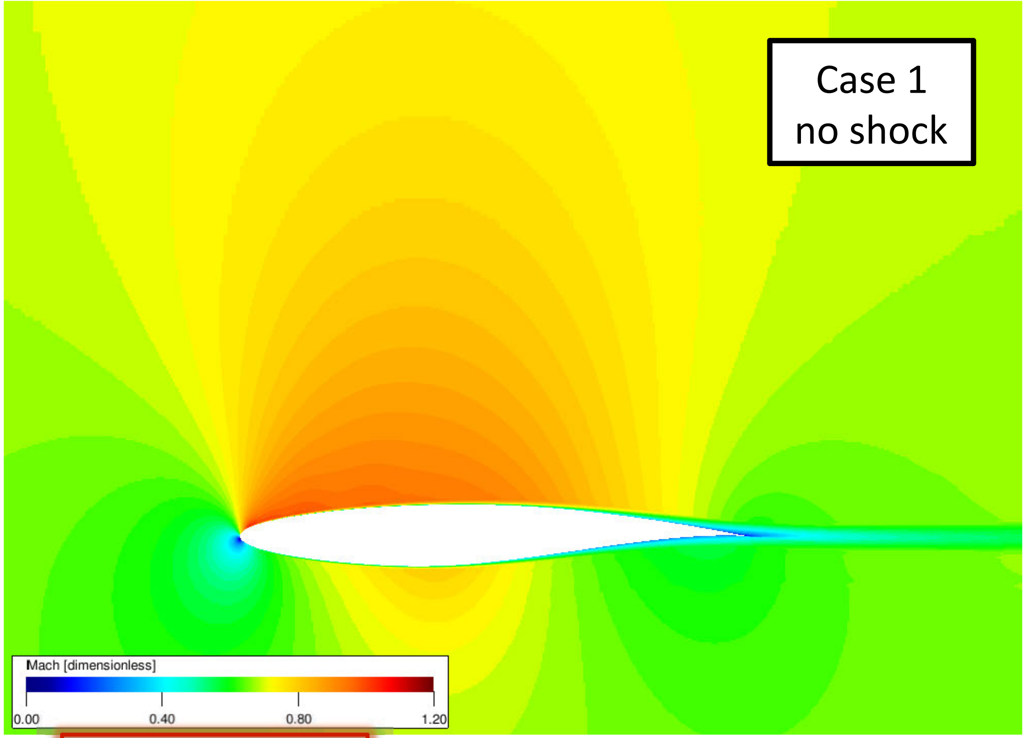
Axisymmetric Transonic Bump Pressure and Skin Friction Distribution





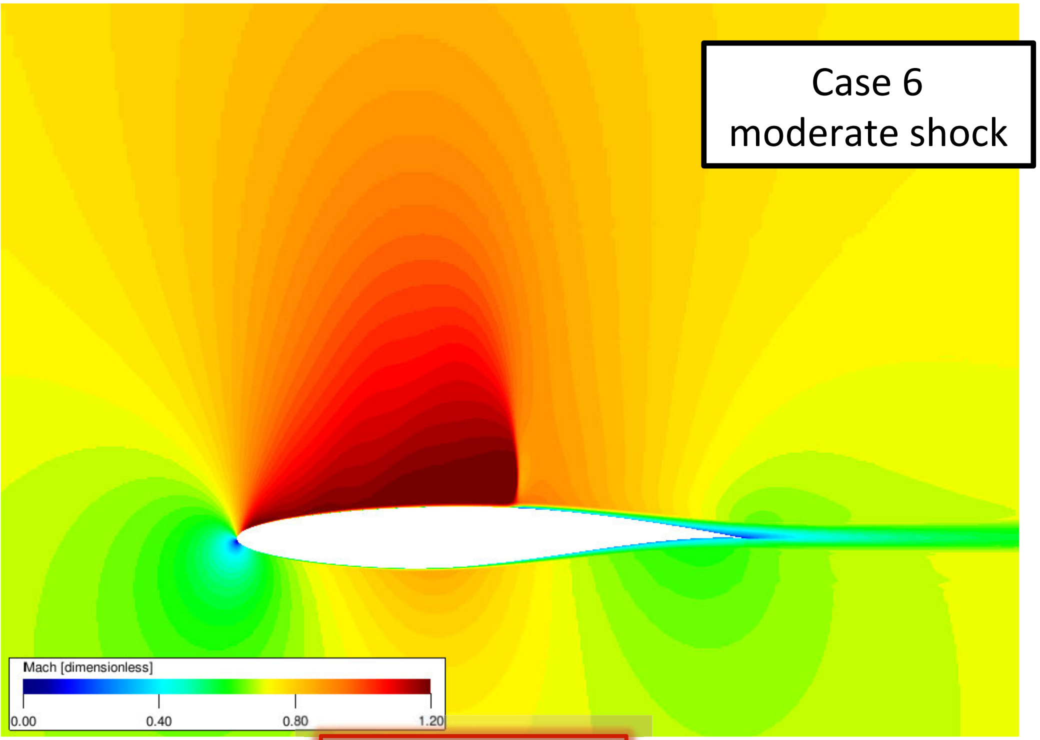
- Unsteady flow in separation after shock captured
- Improved prediction of separation length and skin friction compared to standard RANS

Transonic Flow over the RAE 2822 airfoil



	Case 1	Case 6	Case 9	Case 10
Ma [-]	0.676	0.729	0.73	0.75
AoA [°]	1.8148	2.4508	2.6873	2.7147
Re [10^6]	5.7	6.5	6.5	6.2

Transonic Flow over the RAE 2822 airfoil



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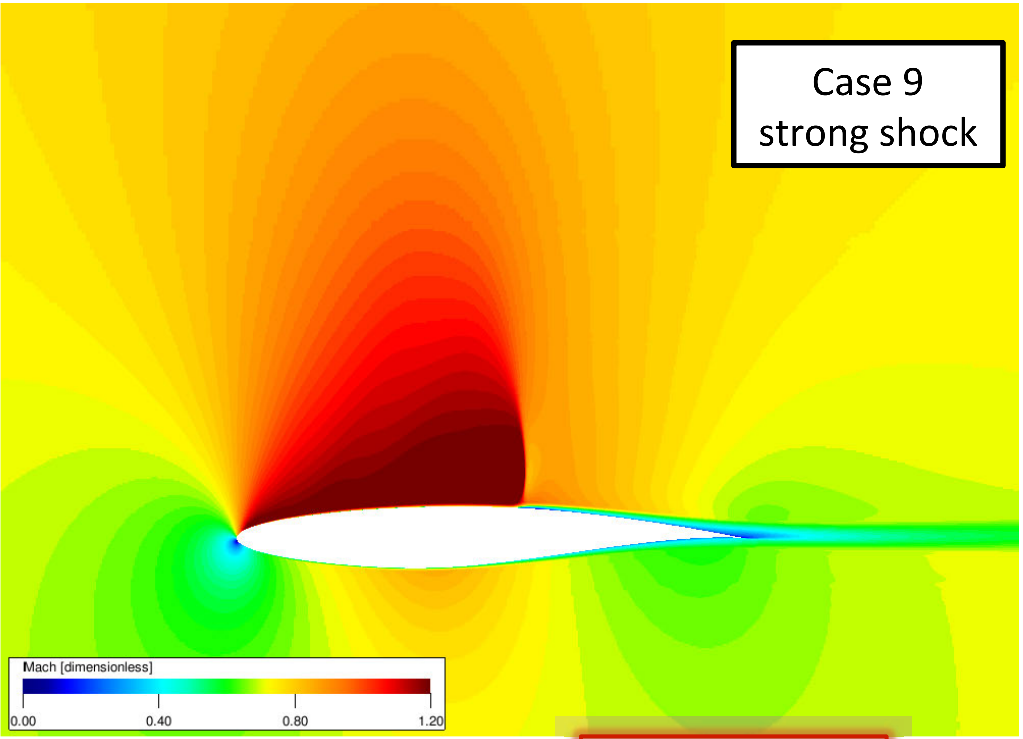

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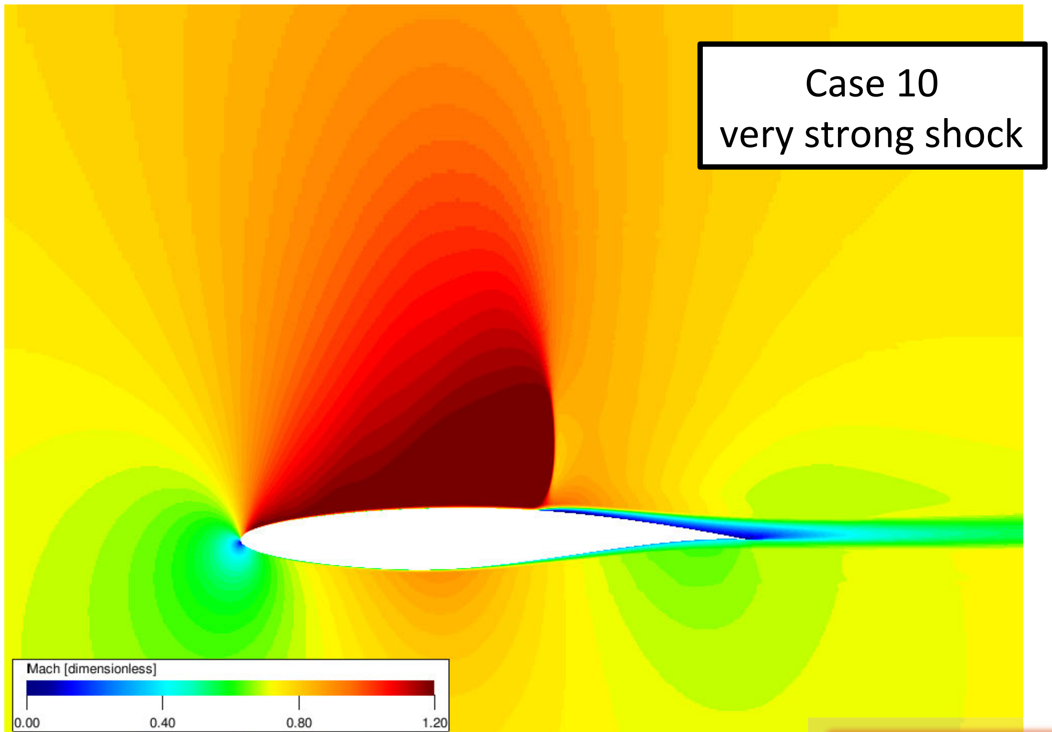
Transonic Flow over the RAE 2822 airfoil



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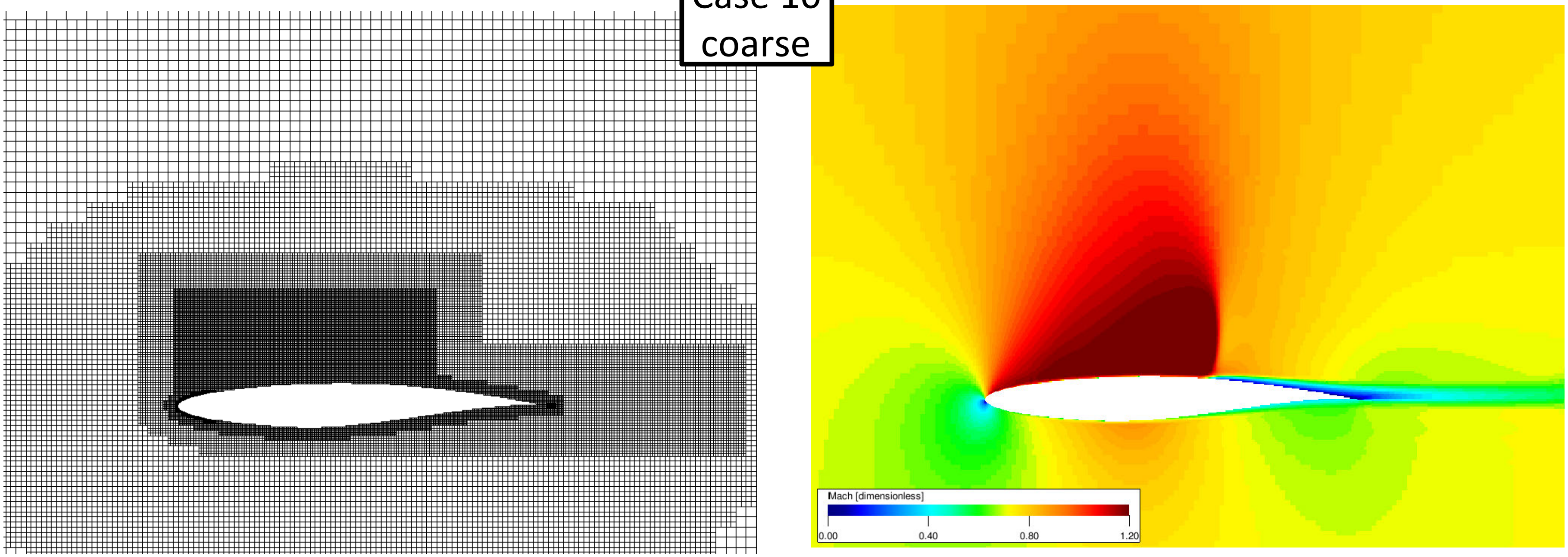
Transonic Flow over the RAE 2822 airfoil

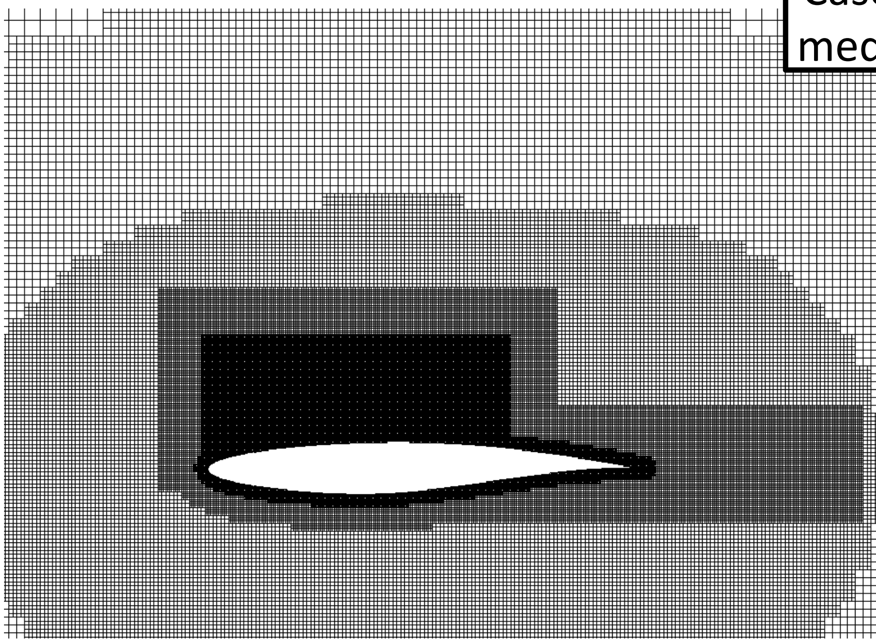
Case 10
coarse

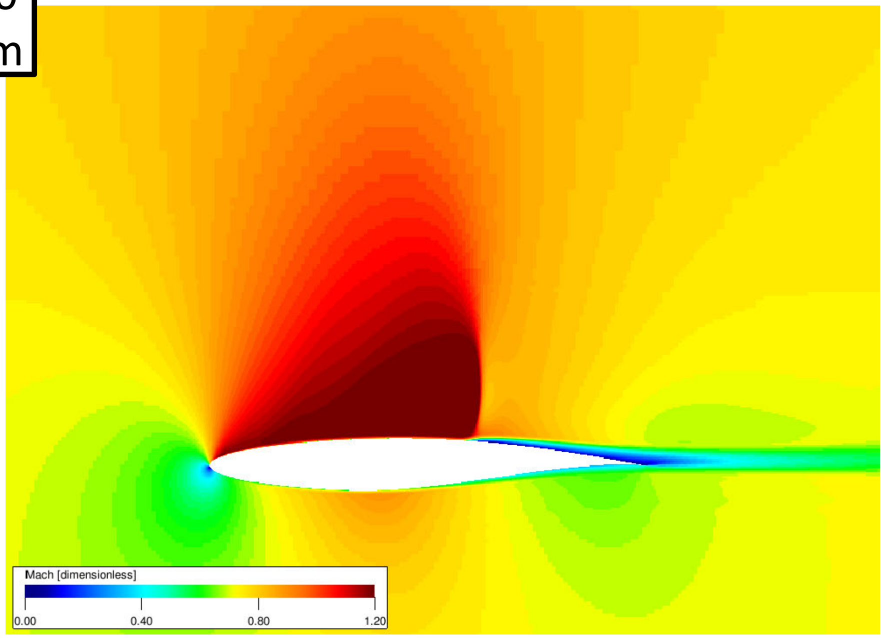


	coarse	Medium	Fine	X-fine	XX-fine
Resolution (cells / chord)	592	888	1333	2000	3000
Voxels [10^3]	63	138	300	667	1500
CPUh	30	65	160	480	1880
Wallclock on 32 cores [h]	1	2	5	15	36

Transonic Flow over the RAE 2822 airfoil

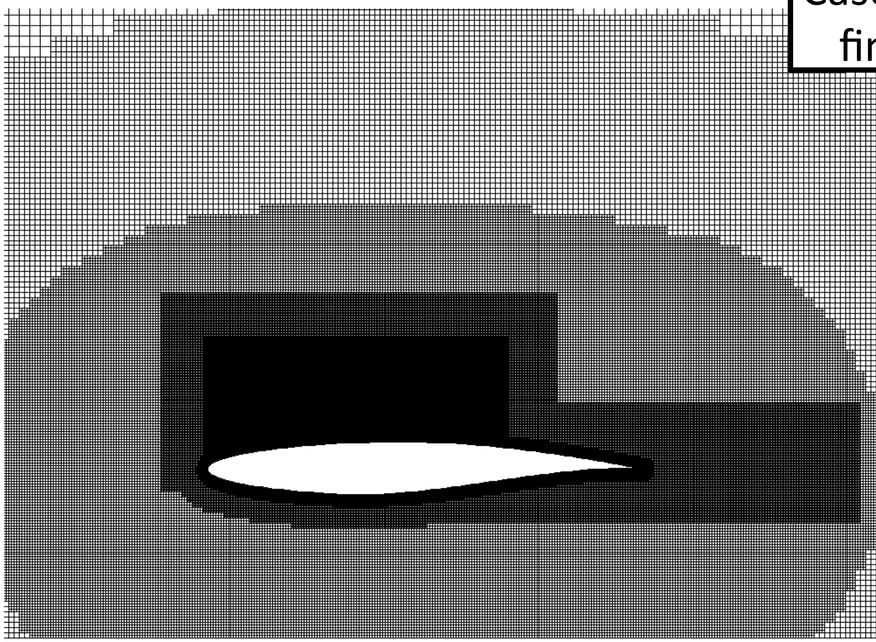
Case 10
medium



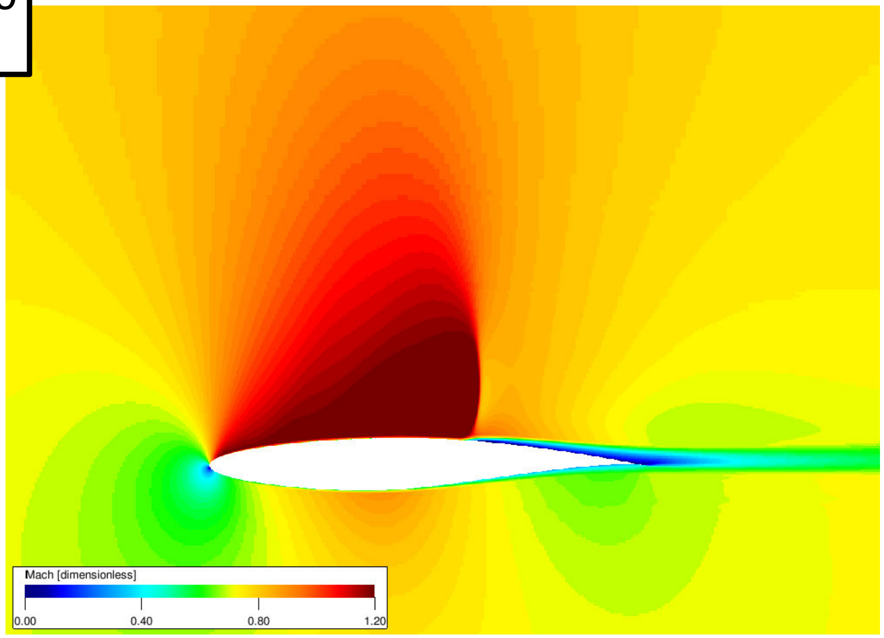


	coarse	Medium	Fine	X-fine	XX-fine
Resolution (cells / chord)	592	888	1333	2000	3000
Voxels [10^3]	63	138	300	667	1500
CPUh	30	65	160	480	1880
Wallclock on 32 cores [h]	1	2	5	15	36

Transonic Flow over the RAE 2822 airfoil



Case 10
fine



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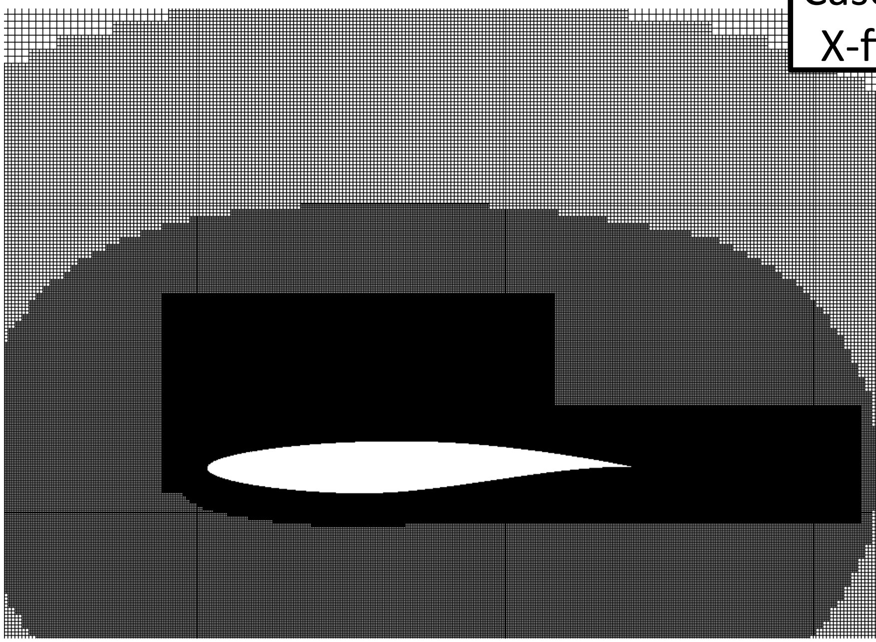
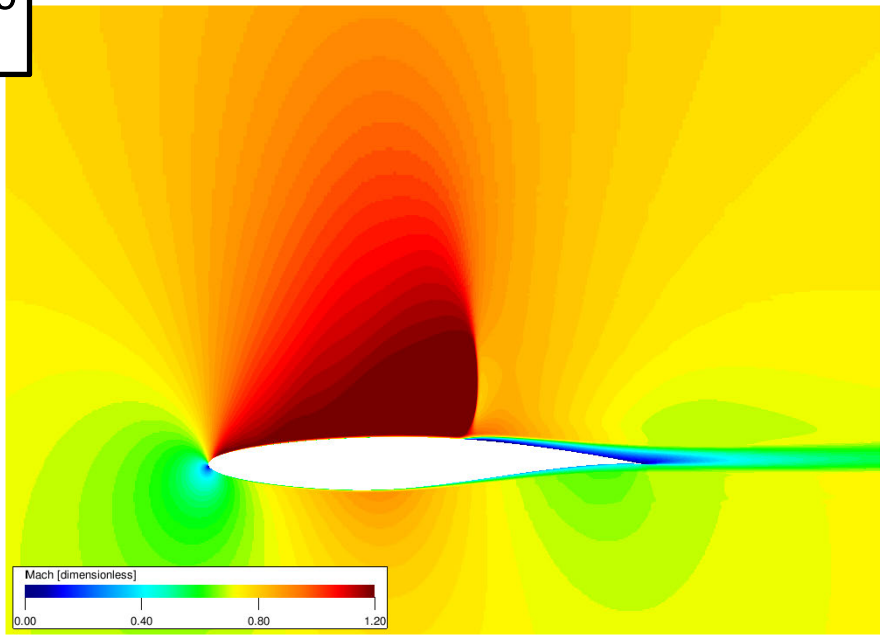
Resolution (cells / chord)	592	888	1333	2000	3000
Voxels [10^3]	63	138	300	667	1500
CPUh	30	65	160	480	1880
Wallclock on 32 cores [h]	1	2	5	15	36

Transonic Flow over the RAE 2822 airfoil

Case 10
X-fine





	coarse	Medium	Fine	X-fine	XX-fine
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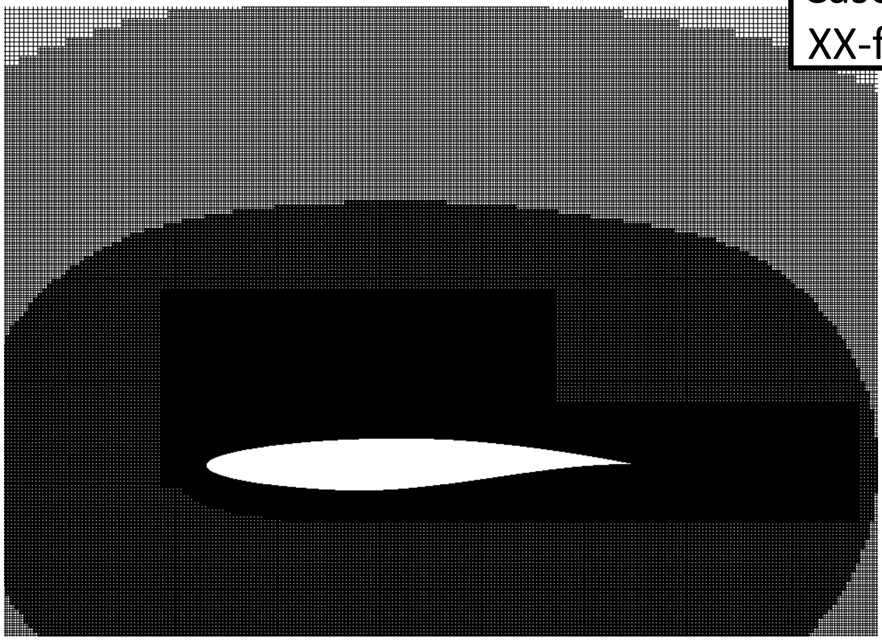
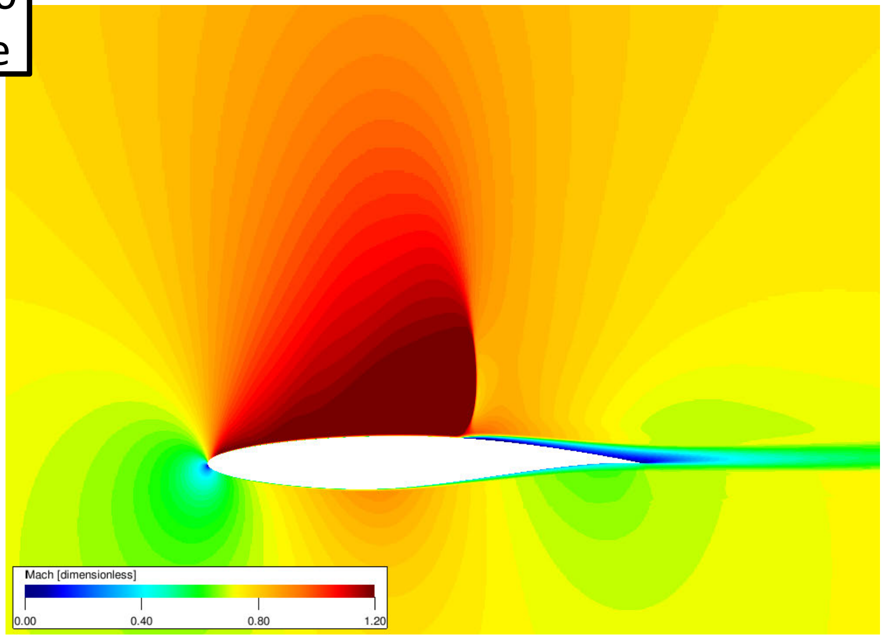
Transonic Flow over the RAE 2822 airfoil

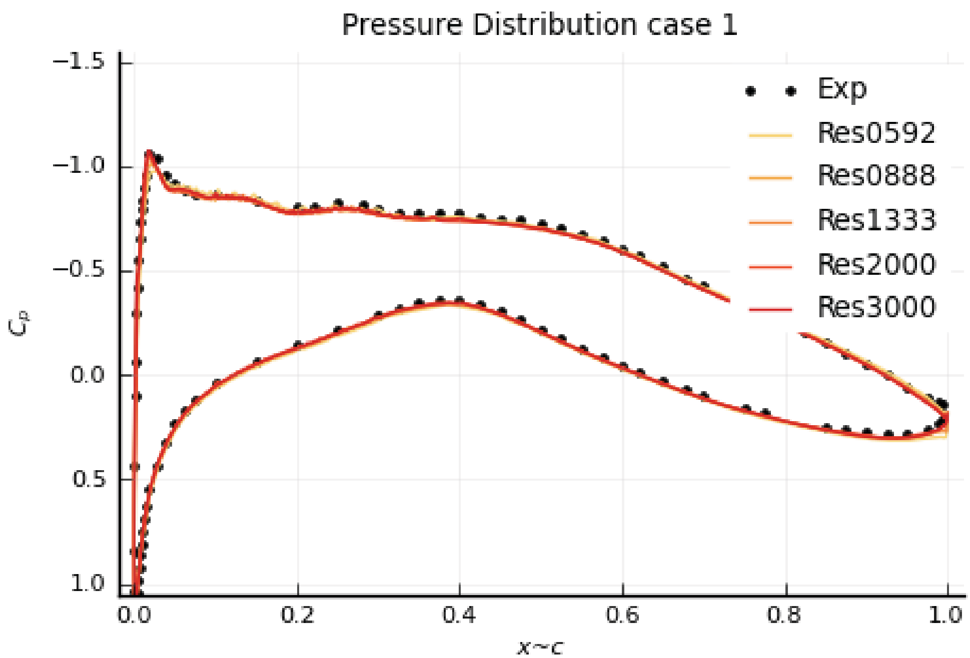
Case 10
XX-fine





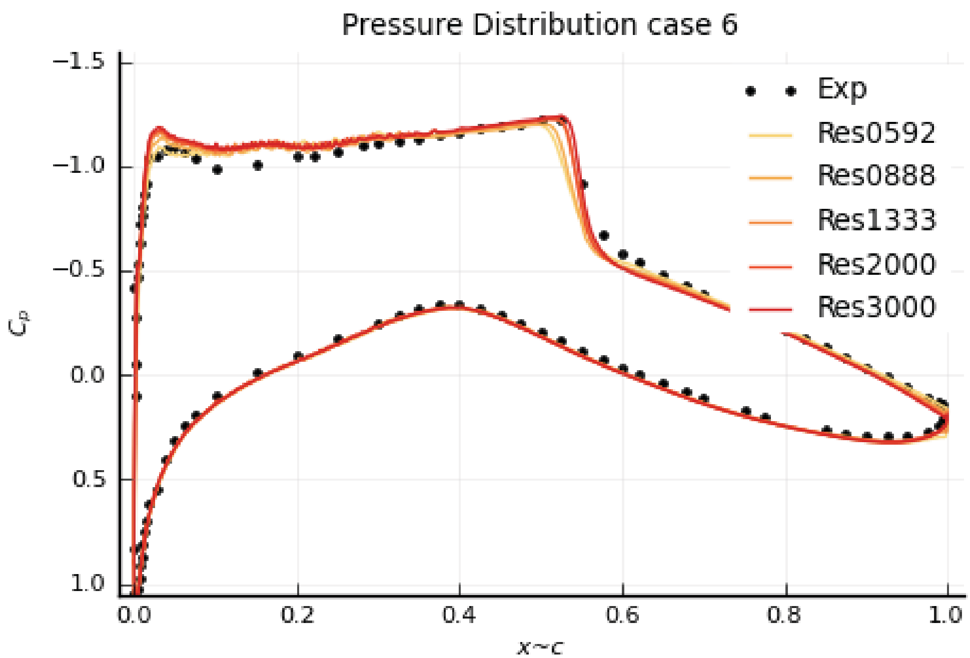
	coarse	Medium	Fine	X-fine	XX-fine
Resolution (cells / chord)	592	888	1333	2000	3000
Voxels [10^3]	63	138	300	667	1500
CPUh	30	65	160	480	1880
Wallclock on 32 cores [h]	1	2	5	15	36

Transonic Flow over the RAE 2822 airfoil



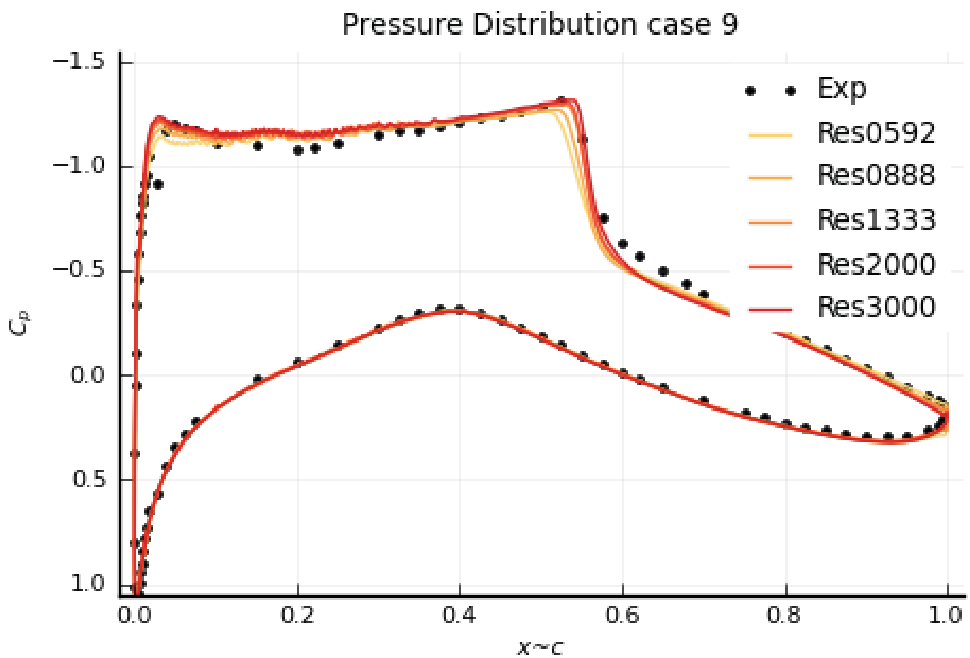
	Case 1	Case 6	Case 9	Case 10
Ma [-]	0.676	0.729	0.73	0.75
AoA [°]	1.8148	2.4508	2.6873	2.7147
Re [10^6]	5.7	6.5	6.5	6.2

Transonic Flow over the RAE 2822 airfoil



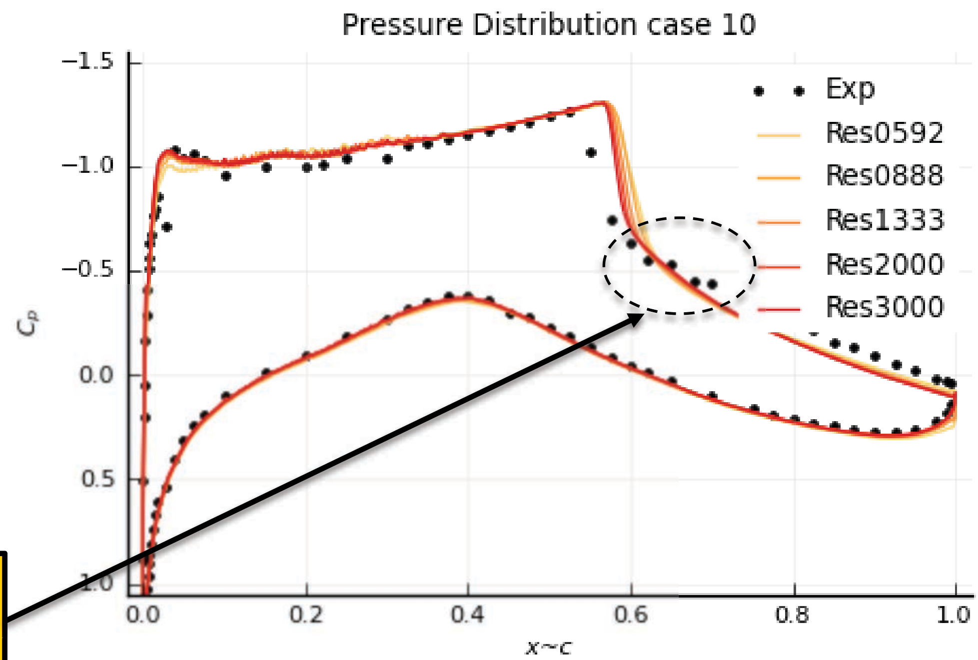
	Case 1	Case 6	Case 9	Case 10
Ma [-]	0.676	0.729	0.73	0.75
AoA [°]	1.8148	2.4508	2.6873	2.7147
Re [10^6]	5.7	6.5	6.5	6.2

Transonic Flow over the RAE 2822 airfoil



	Case 1	Case 6	Case 9	Case 10
Ma [-]	0.676	0.729	0.73	0.75
AoA [°]	1.8148	2.4508	2.6873	2.7147
Re [10^6]	5.7	6.5	6.5	6.2

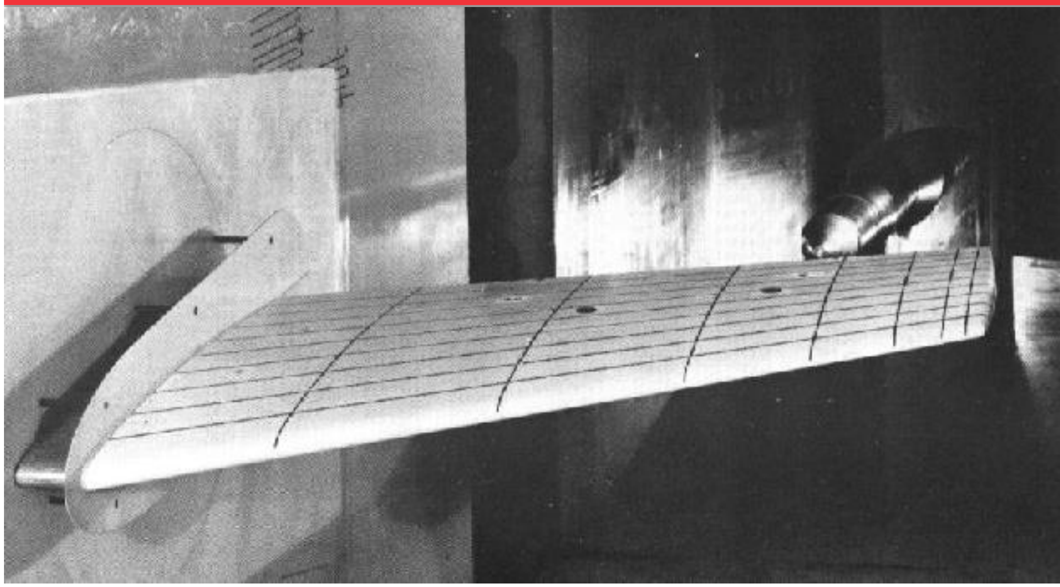
Transonic Flow over the RAE 2822 airfoil



shock-induced separation expected to be better captured in 3D

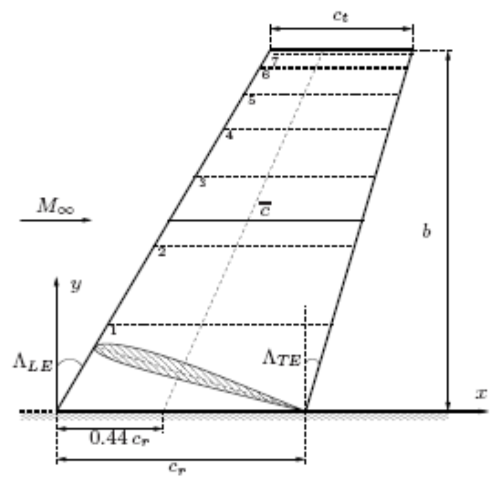
	Case 1	Case 6	Case 9	Case 10
Ma [-]	0.676	0.729	0.73	0.75
AoA [°]	1.8148	2.4508	2.6873	2.7147
Re [10^6]	5.7	6.5	6.5	6.2

3D Onera-M6



Span, **b**	1.1963 meters
Mean Aerodynamic Chord, **c**	0.64607 meters
Aspect Ratio	3.8
Taper Ratio	0.562
Leading-edge Sweep	30.0 degrees
Trailing-edge Sweep	15.8 degrees

Mach #	Reynolds #	AoA
0.84	11.72E6	3.06

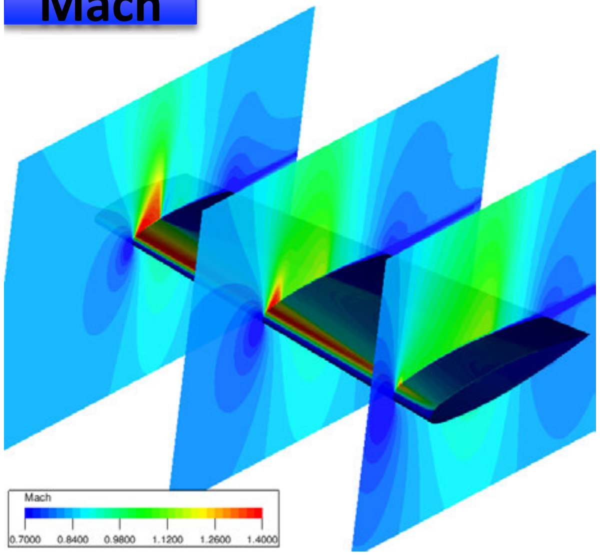


Geometry	
AR	3.8
b	$1.196\ m$
Λ_{LE}	30°
Λ_{TE}	15.8°
λ	0.562
$\bar{c}$	$0.646\ m$
S	$1.506\ m^2$

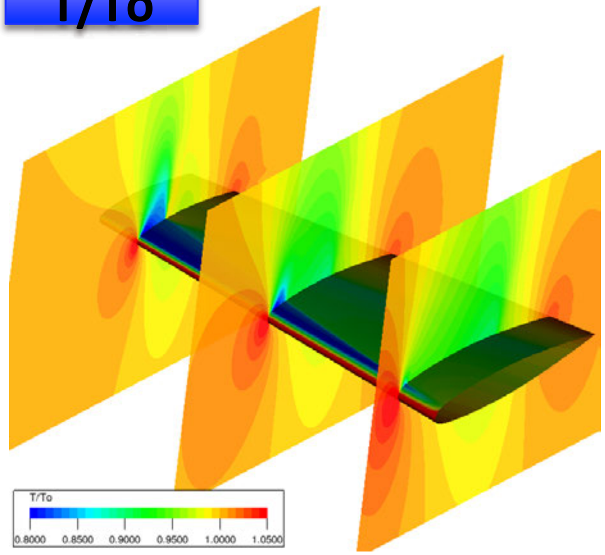
Exa

Flow-field Images

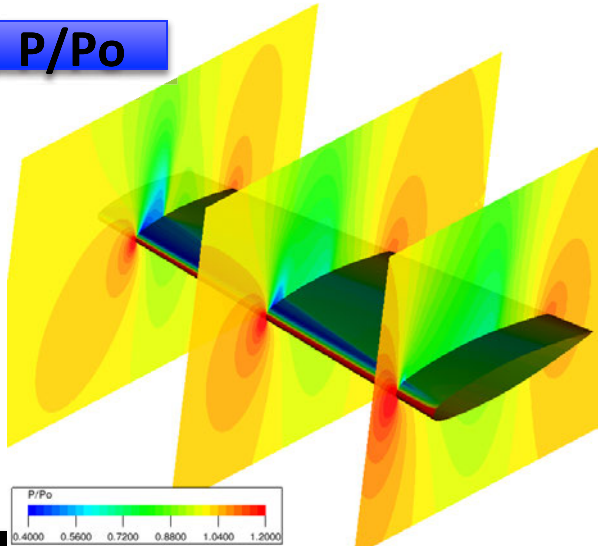
Mach



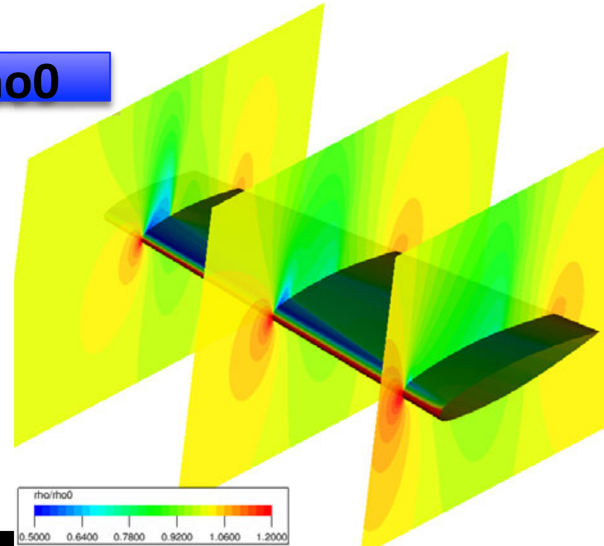
T/To



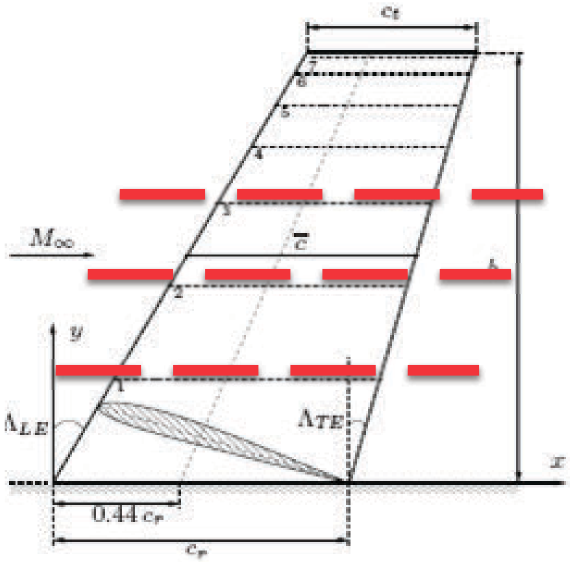
P/Po

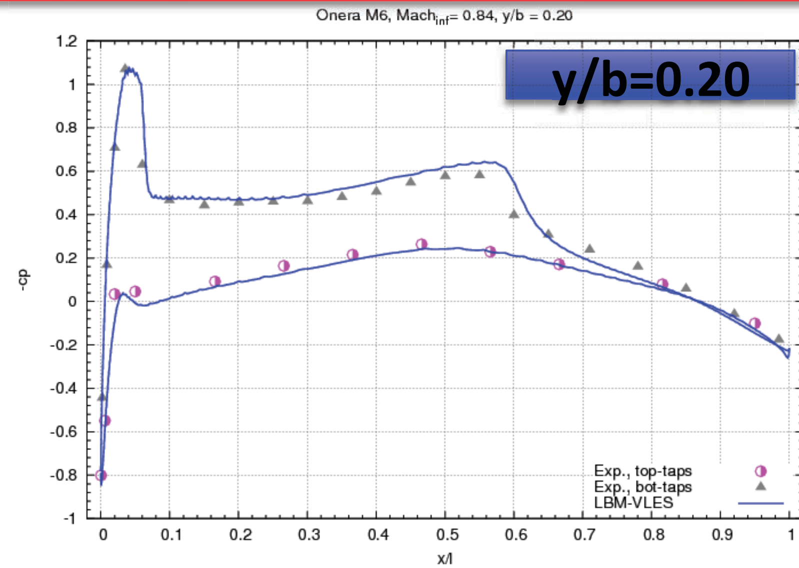


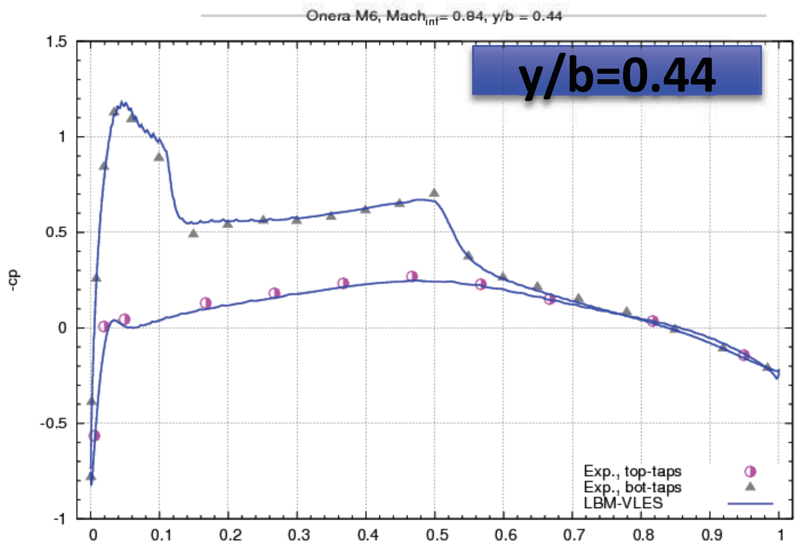
rho/rho0

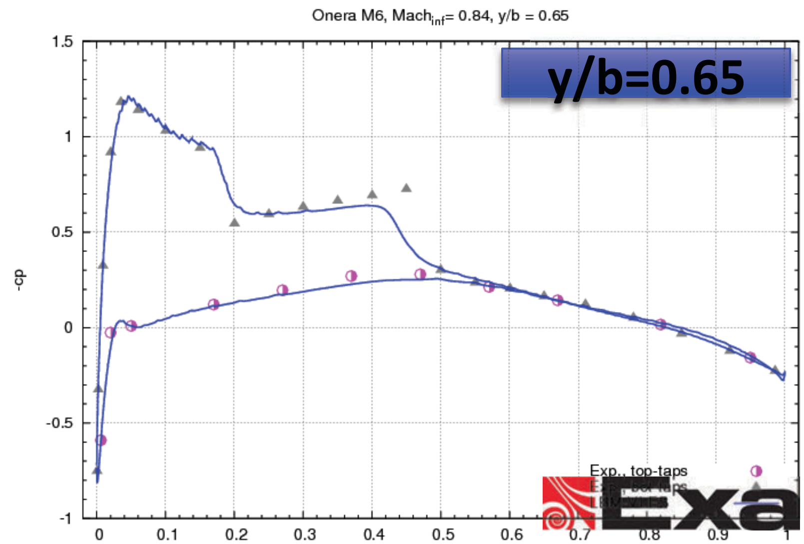


3D Onera-M6
Sectional Cp on Surface



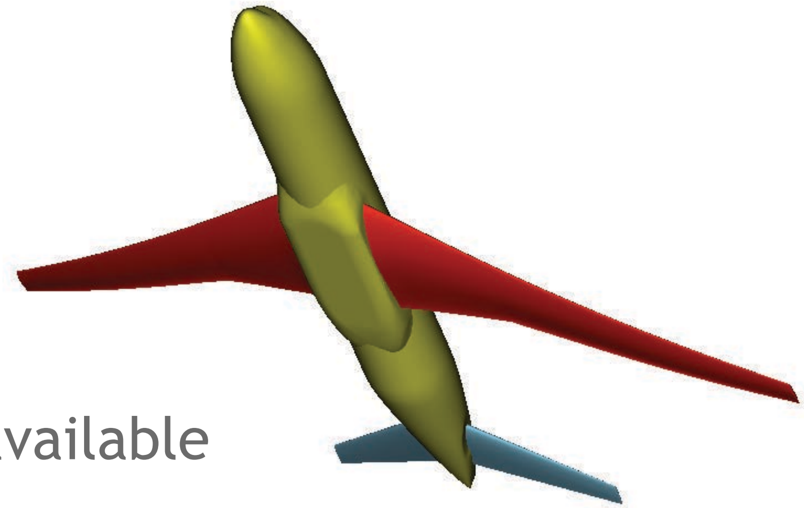






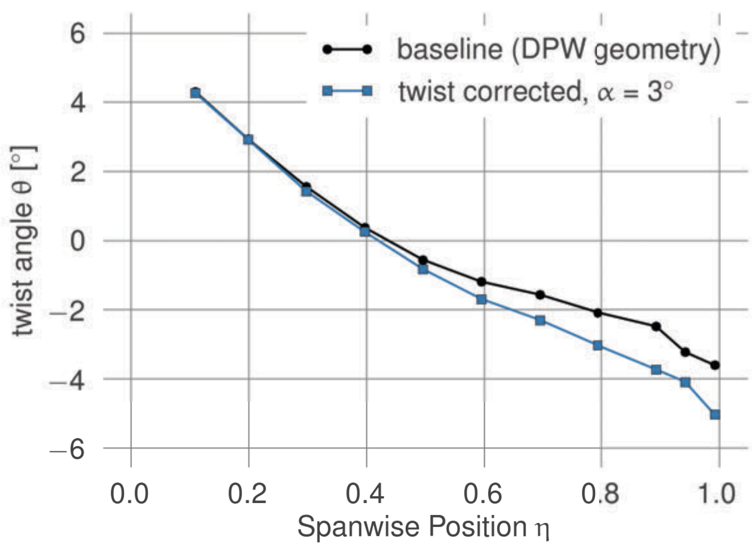
NASA-CRM Model

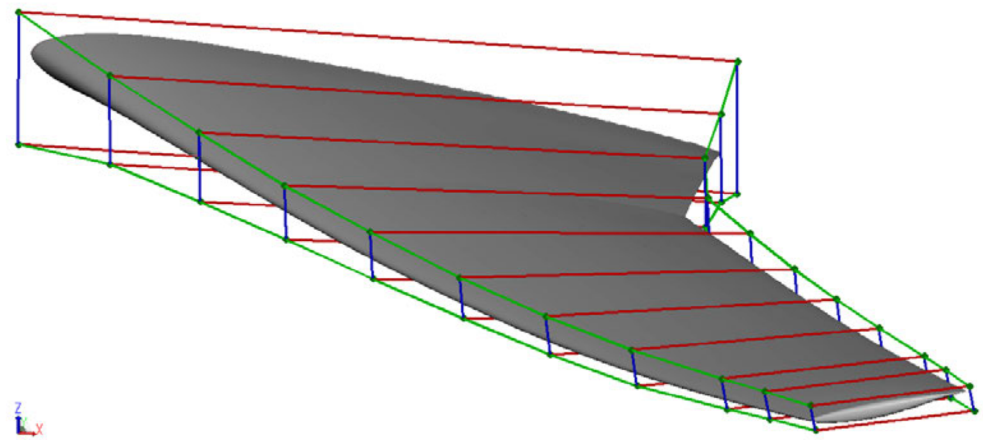
- DPW4 Geometry
  - *Reference CFD Data*
  - *Wing-body & tail*
    - Supercritical wing
    - Built to the design-shape
    - Twist correction information available



- Measured at several Windtunnels
  - ***ETW*, *NTF*, *NASA Ames 11ft, JAXA JTWT***

Wing Twist Correction

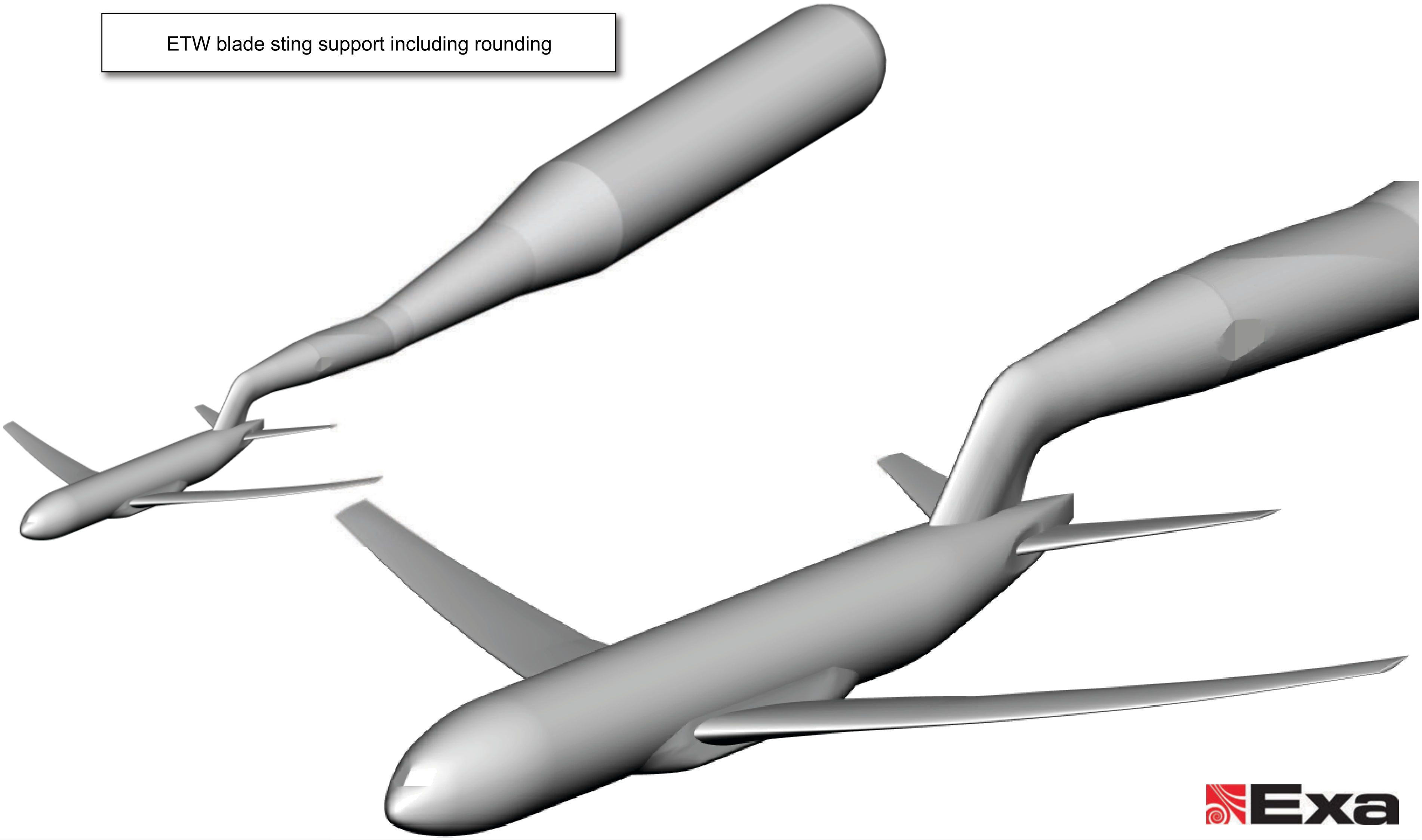




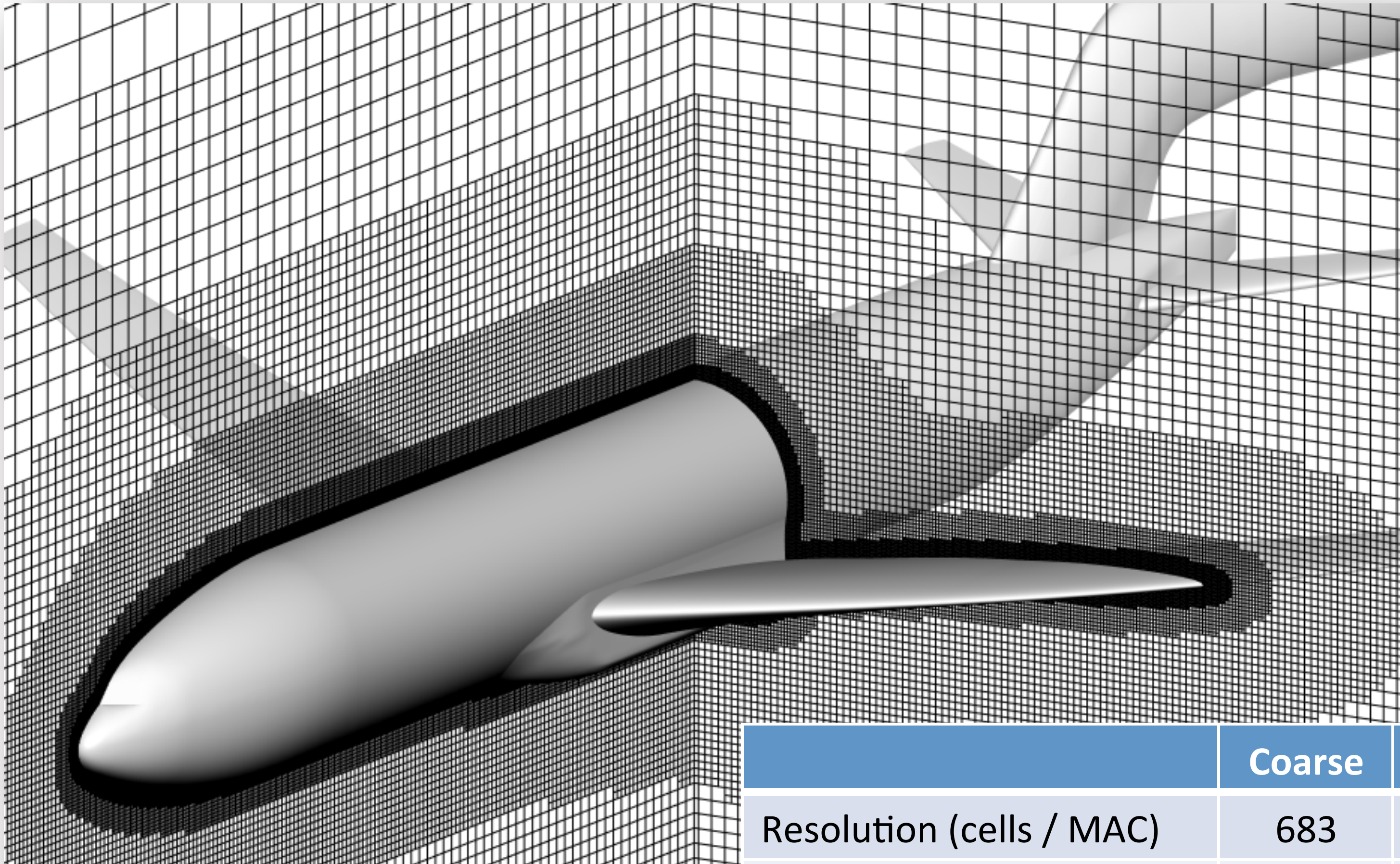
PowerDELTA® morphing

Simulated Geometry

ETW blade sting support including rounding



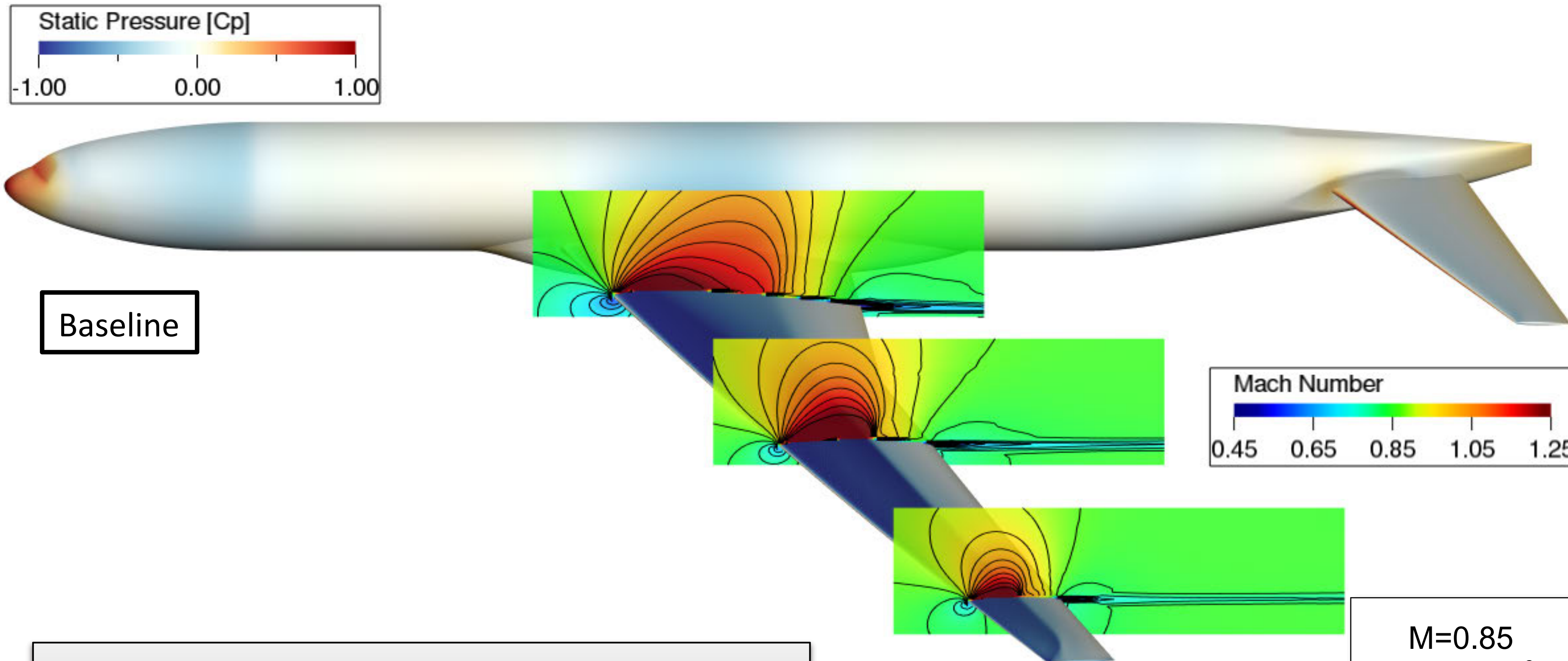
Computational Mesh*



	Coarse	Medium	Fine
Resolution (cells / MAC)	683	1024	1536
Voxels [10^6]	30	88	274
CPUh [10^3]	5.4	17	38
Wallclock on 360 cores [d]	0.6	2	4.4

* Simulated with Symmetry
* additional resolution to resolve sting negligible

Results



Baseline

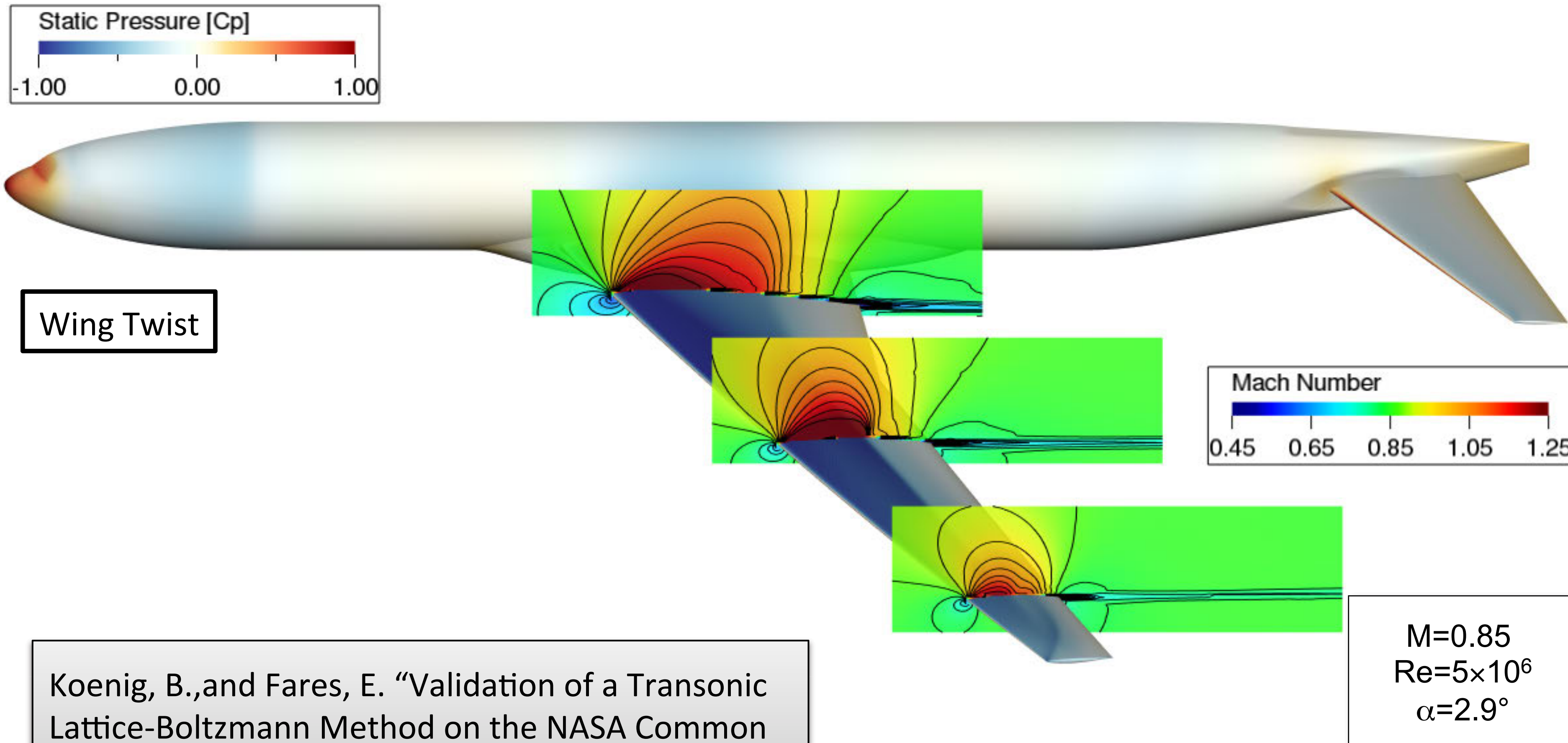
M=0.85
Re=5×10^6
α=2.9°

Koenig, B.,and Fares, E. "Validation of a Transonic Lattice-Boltzmann Method on the NASA Common Research Model", AIAA 2023-2016.

Exa

Results

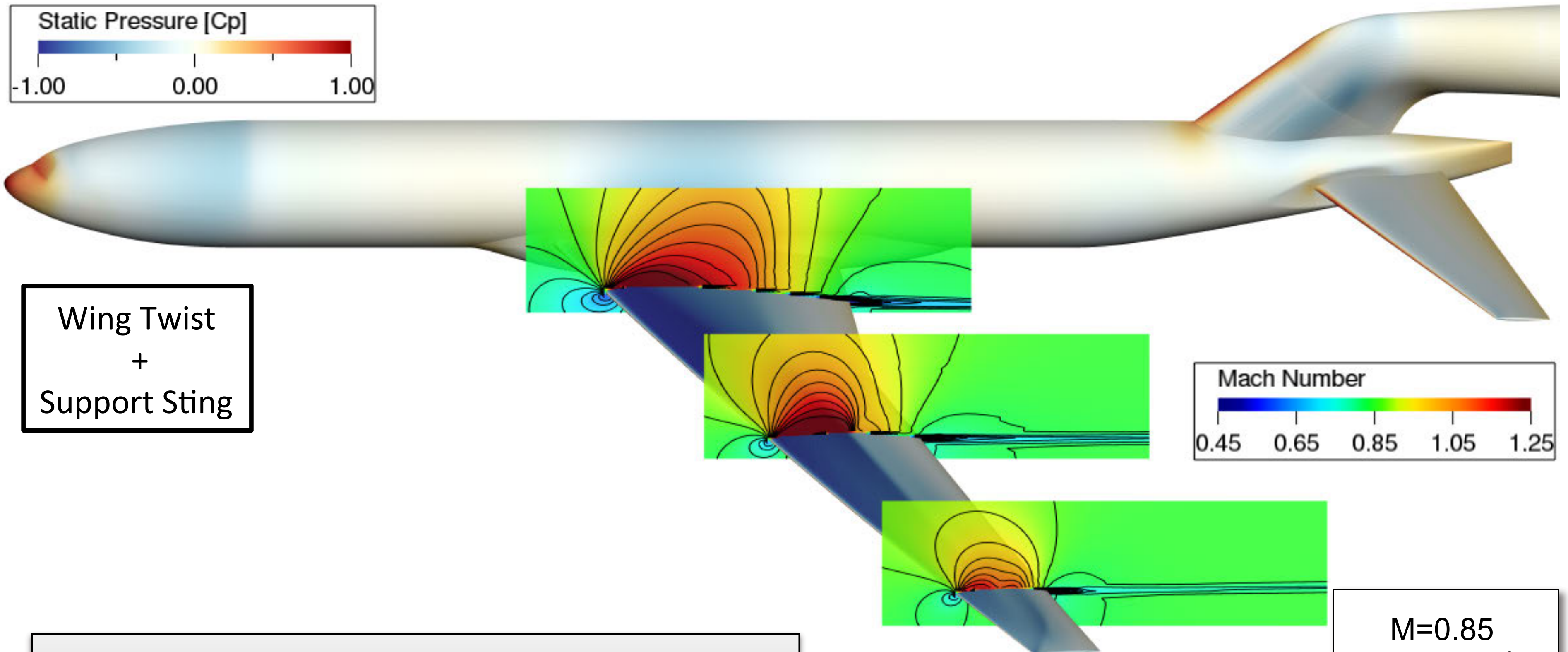
- DPW4 Geometry (NASA CRM model)



Koenig, B.,and Fares, E. "Validation of a Transonic Lattice-Boltzmann Method on the NASA Common Research Model", AIAA 2023-2016.

Results

- DPW4 Geometry (NASA CRM model)

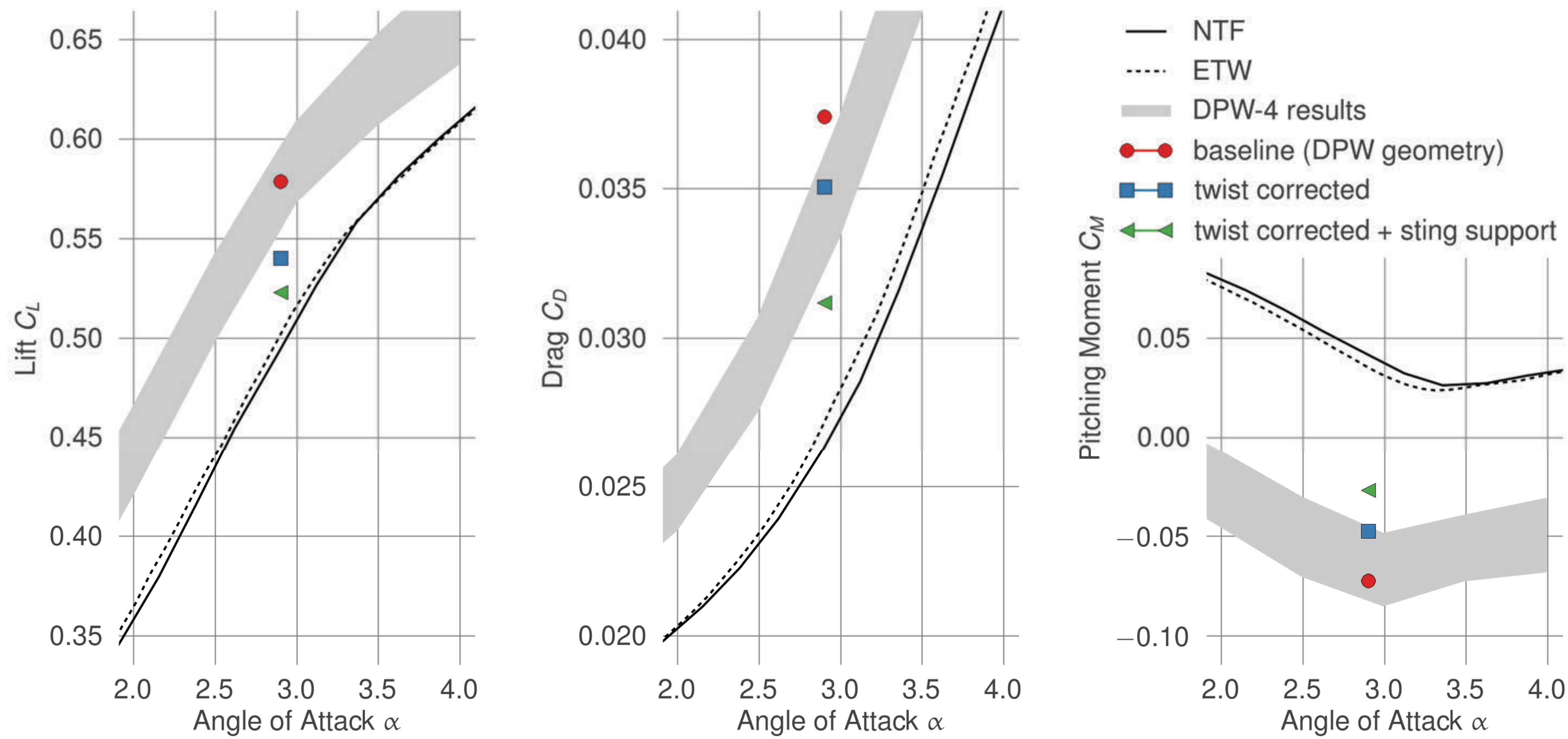


Wing Twist
+
Support Sting

M=0.85
Re=5×10^6
α=2.9°

Koenig, B.,and Fares, E. "Validation of a Transonic Lattice-Boltzmann Method on the NASA Common Research Model", AIAA 2023-2016.

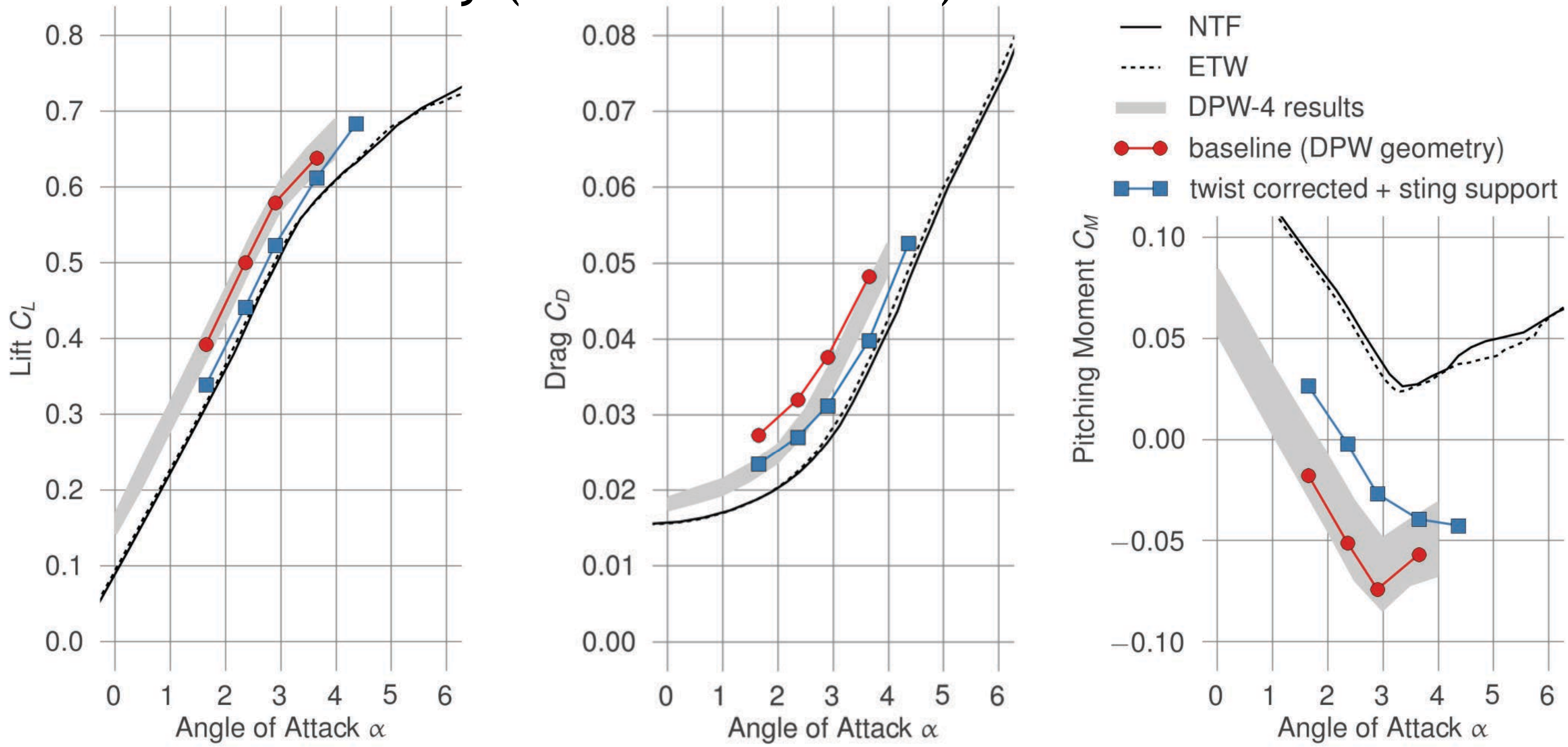
Results – Wing Twist and Sting Effects



M=0.85
Re=5×10^6

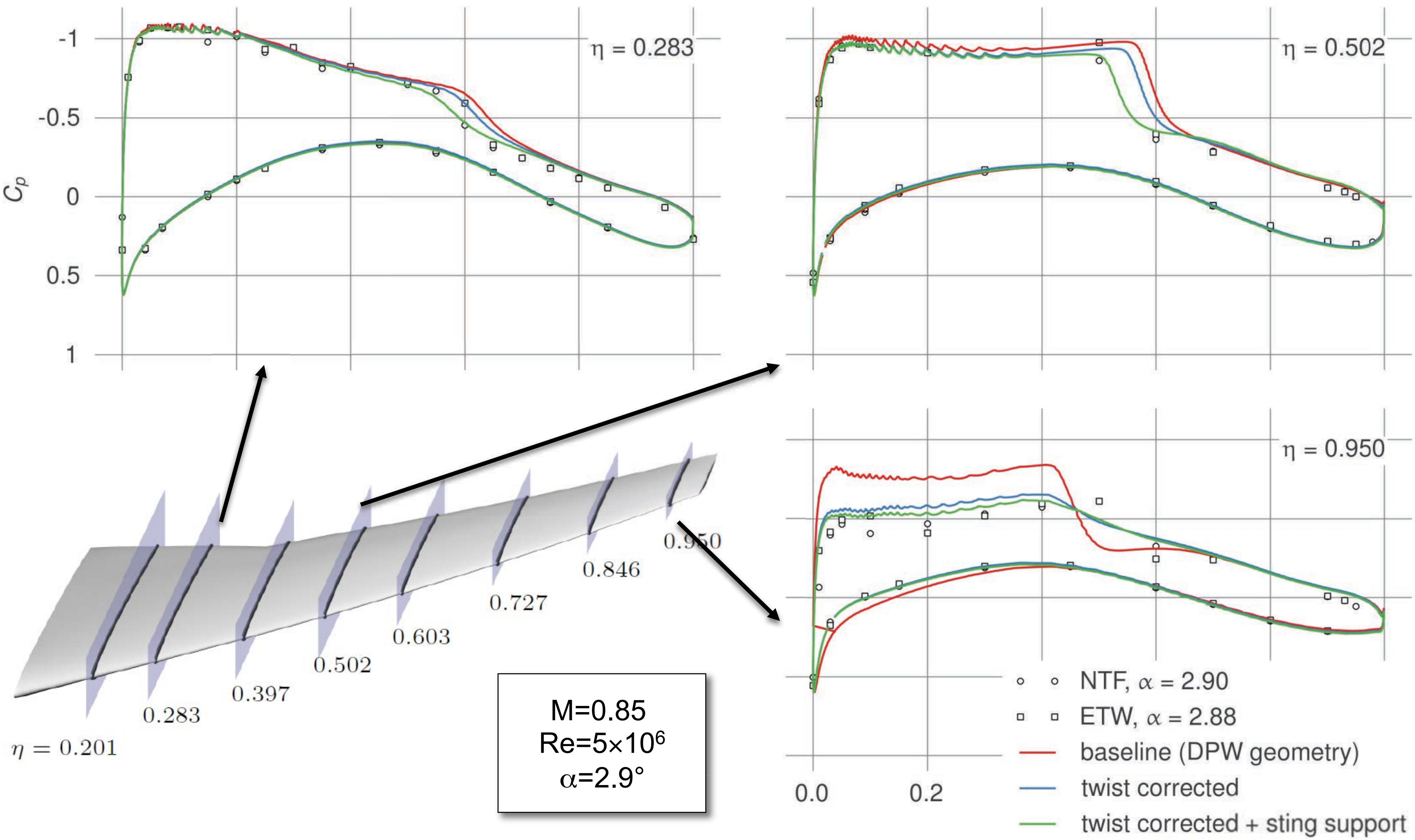
Results – Wing Twist and Sting Effects

- DPW4 Geometry (NASA CRM model)



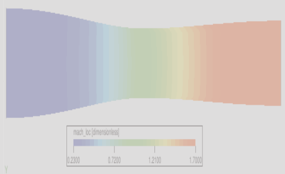
M=0.85
Re=5×10^6

Results – Wing Twist and Sting Effects



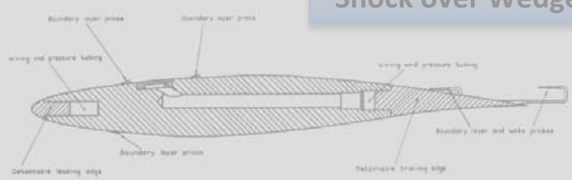
Transonic Code Validation & Application

Fundamental Validations

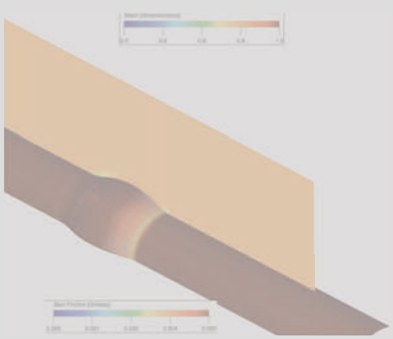


CDV nozzle

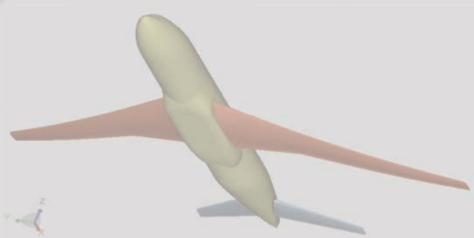
Shock over Wedge



RAE 2822 Airfoil

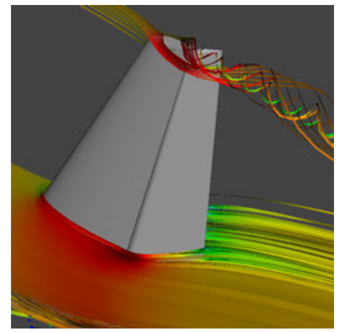


Transonic Bump

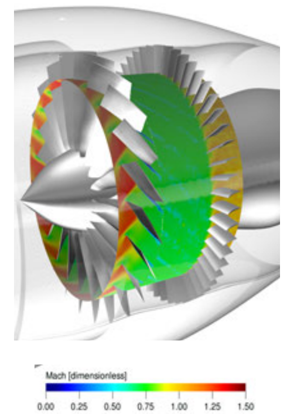


CRM

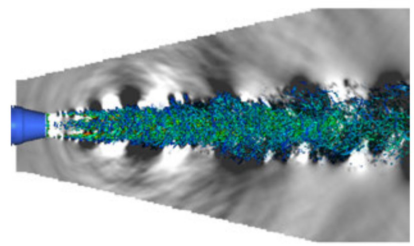
Industrial Applications



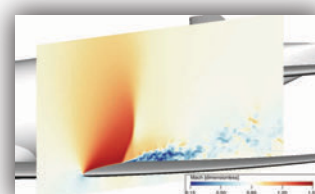
Flow Control



Fan Noise

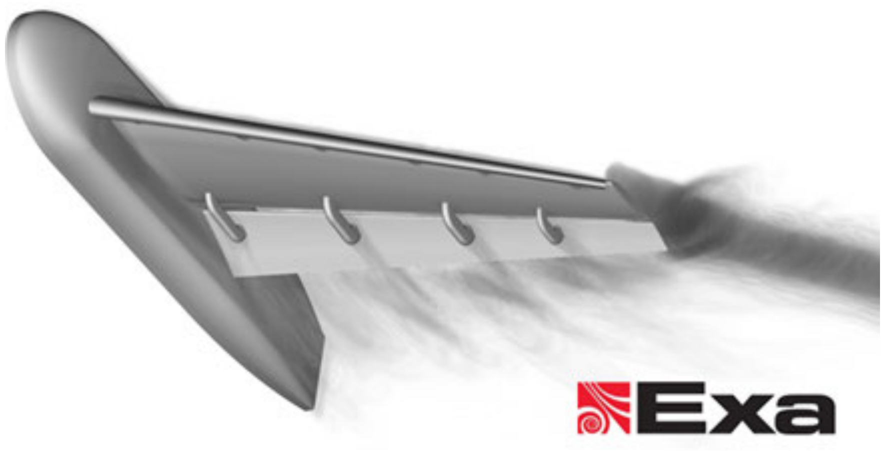


Jet Noise



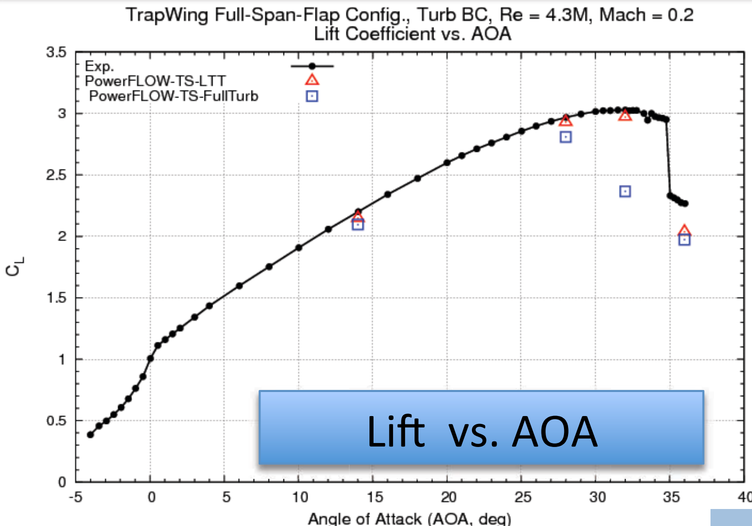
Buffet

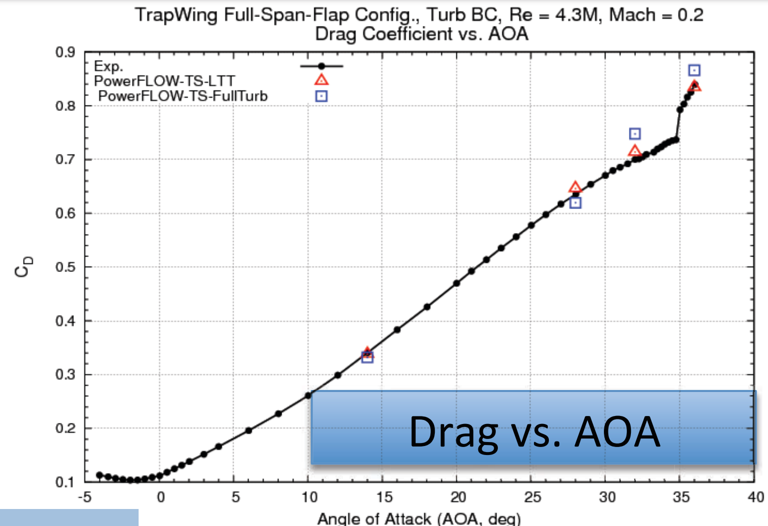
Trapezoidal Wing FSF Configurations



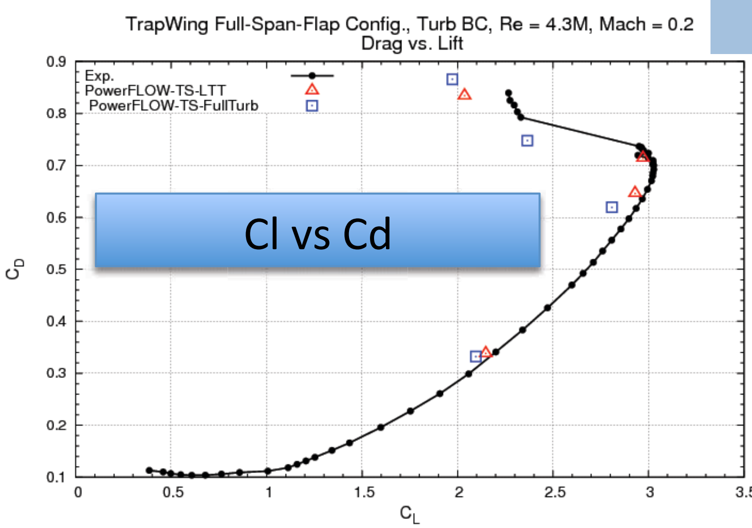
- **Full Span Flap (FSF) Configuration**
- **Re = 4.3 M**
- **Mach = 0.2**
- **Laminar to turbulence transition (LTT) included**

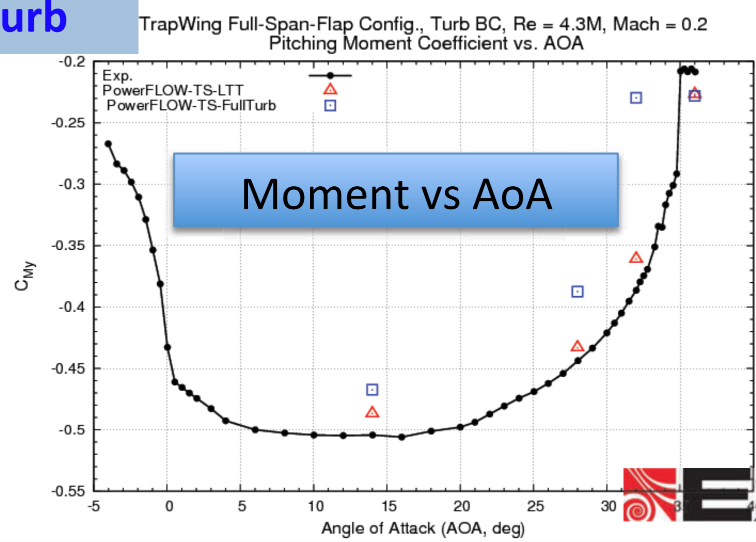
TrapWing : Drag & Lift





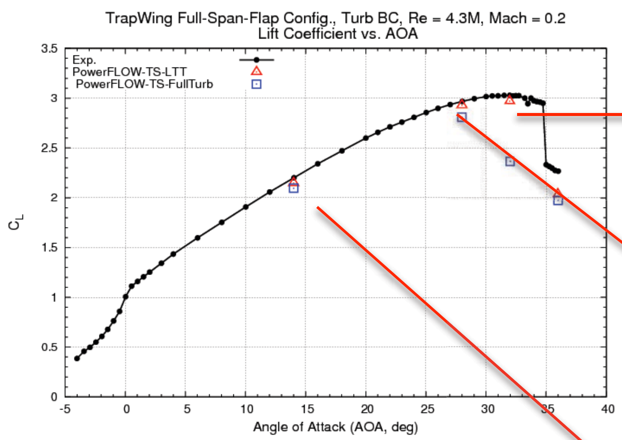
LTT
Full-Turb

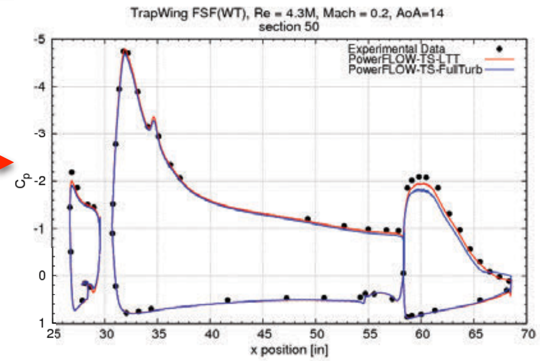


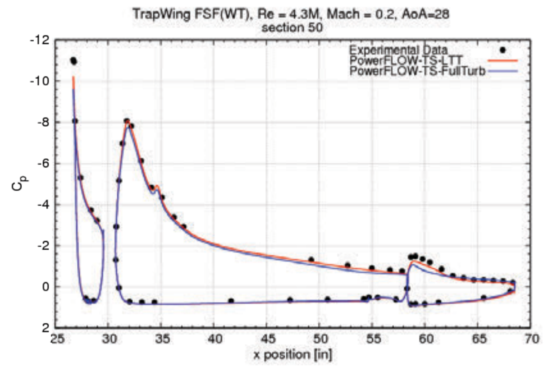


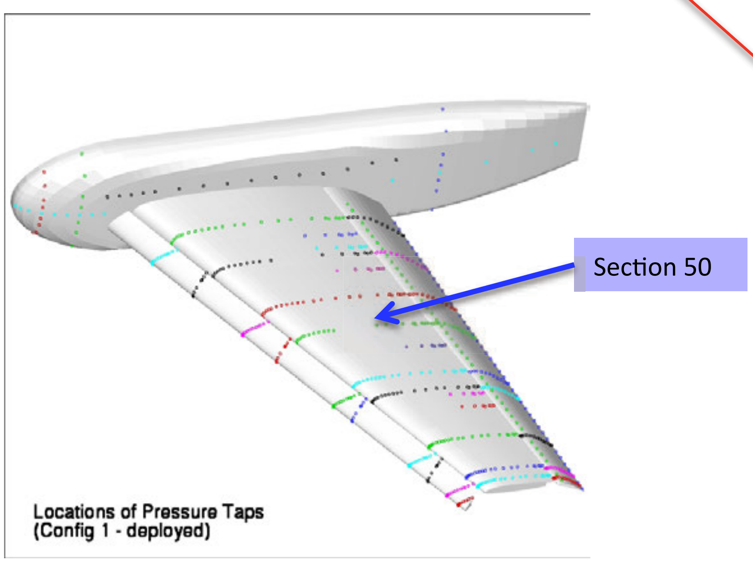
Sectional Surface Pressure

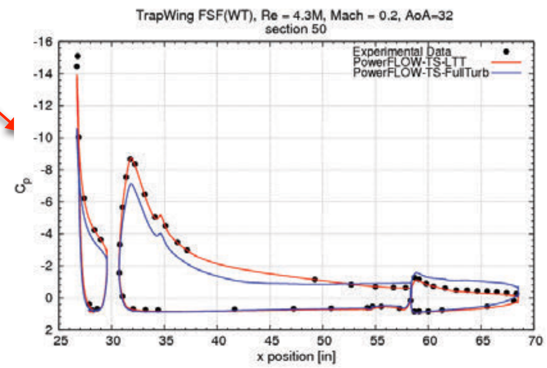
LTT
Full-Turb



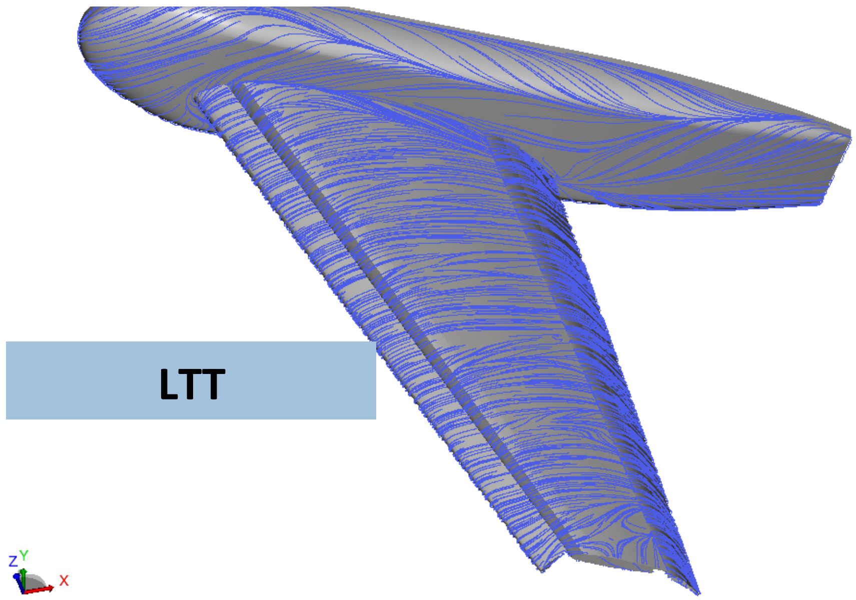


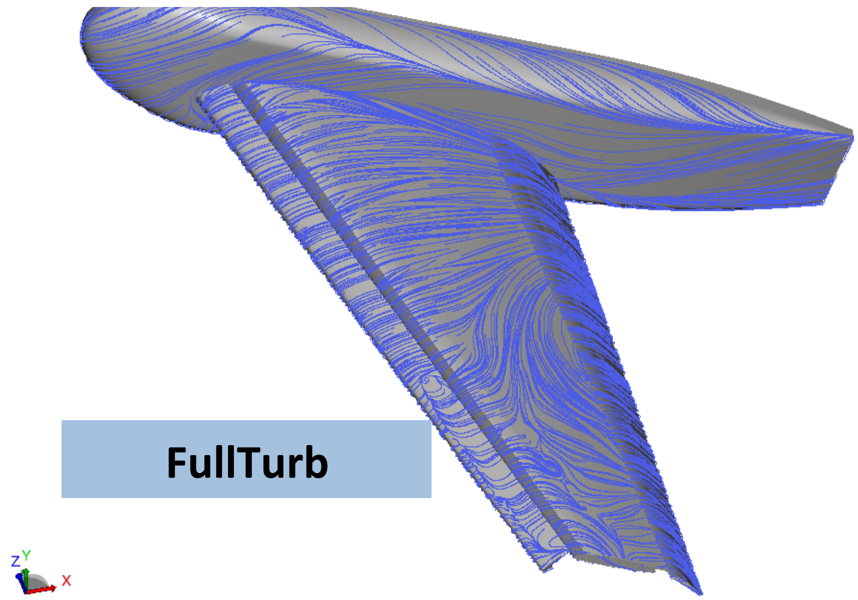






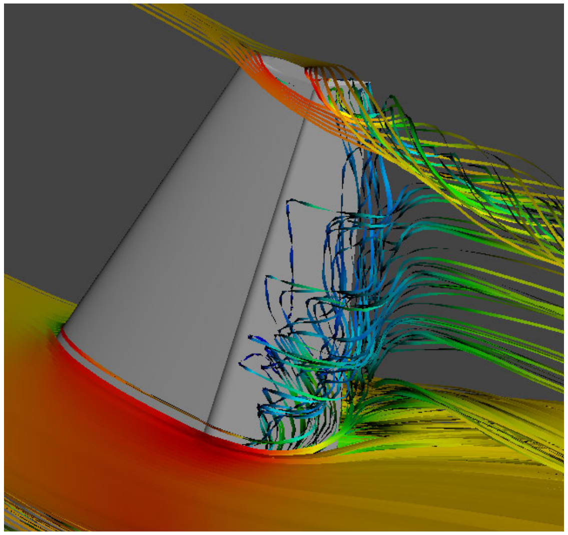
Surface Streamlines – AoA 32



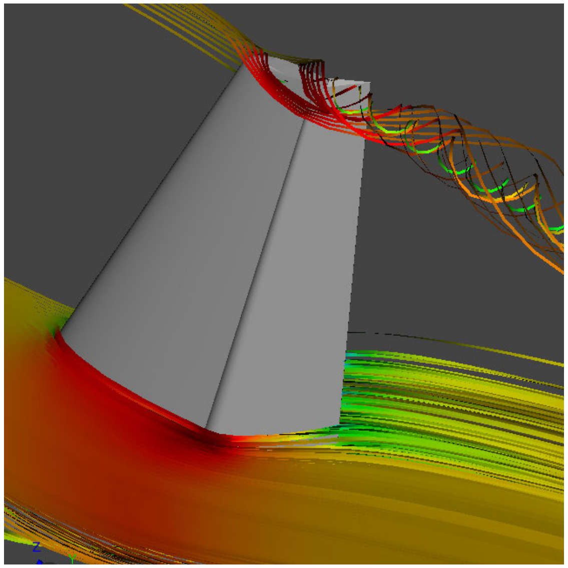


NASA - Active Flow Control

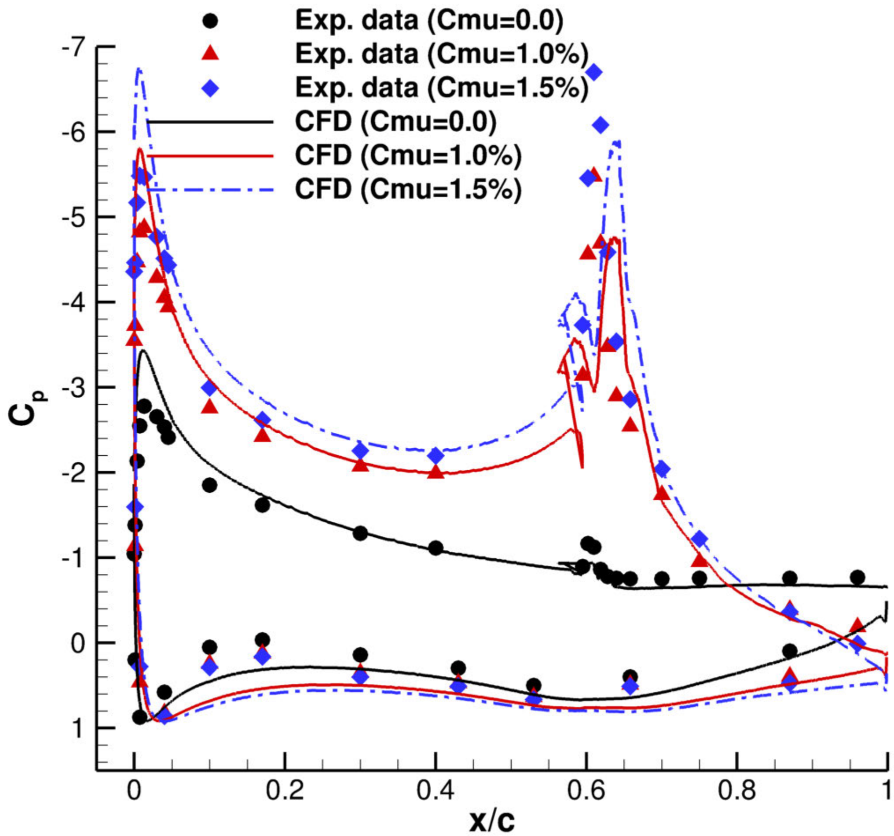
Unactuated, Cmu=0.0



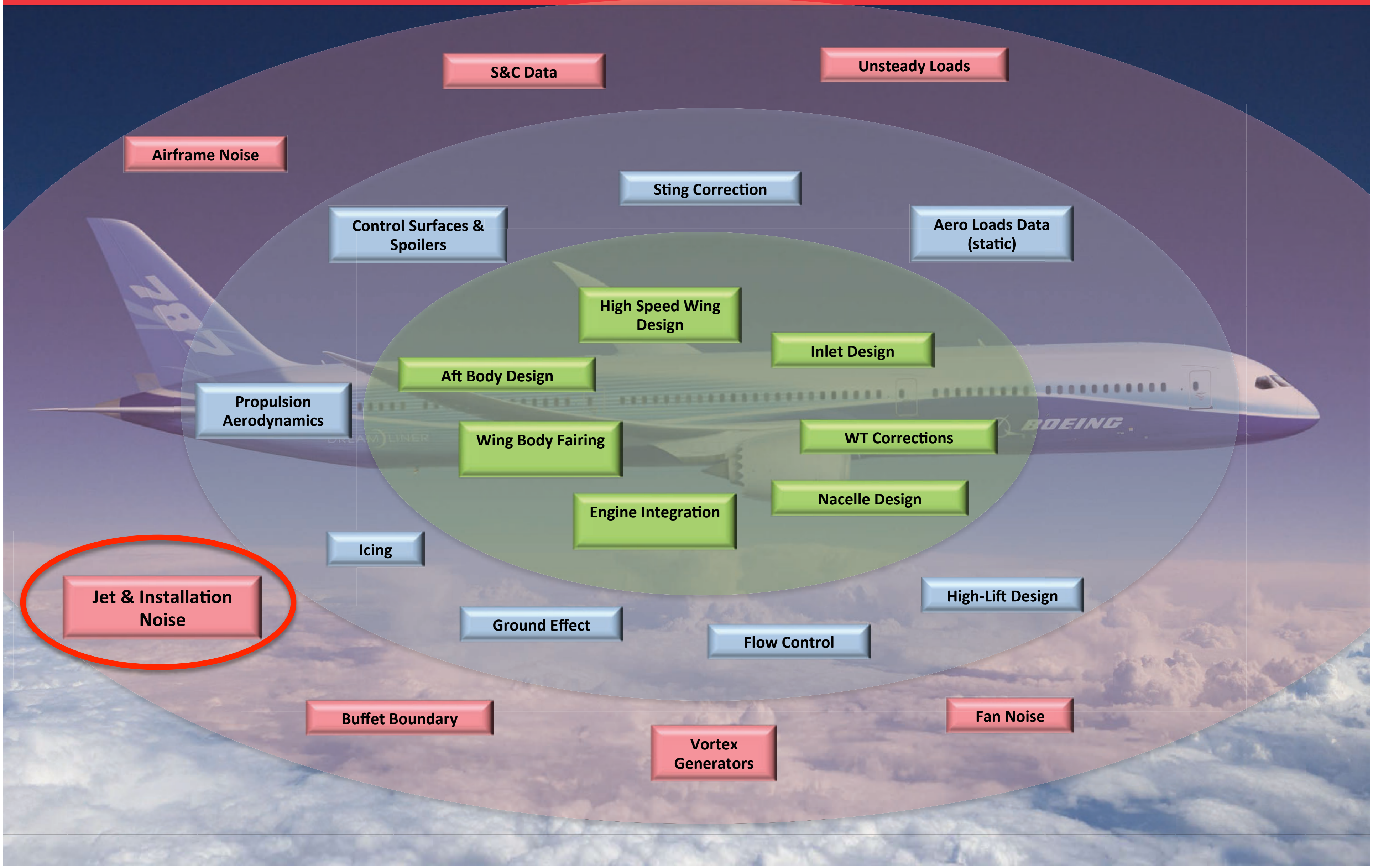
Actuated, Cmu=1.5%



C_p at 89% span

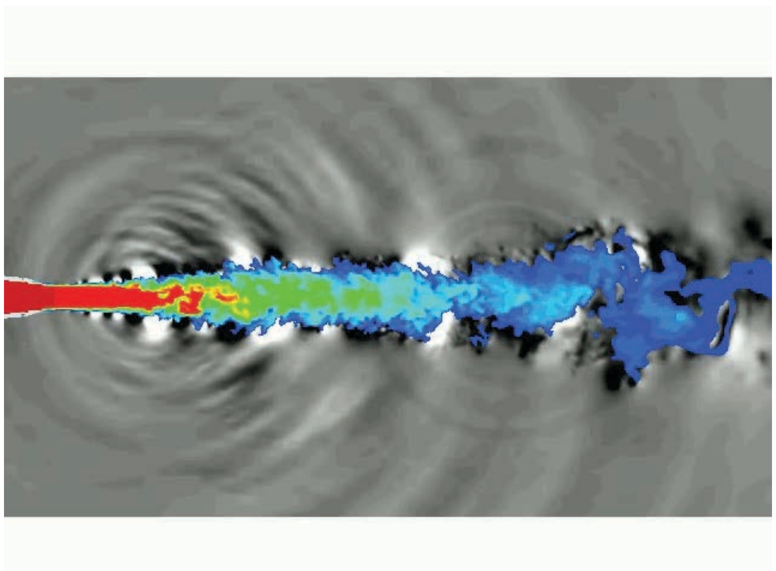


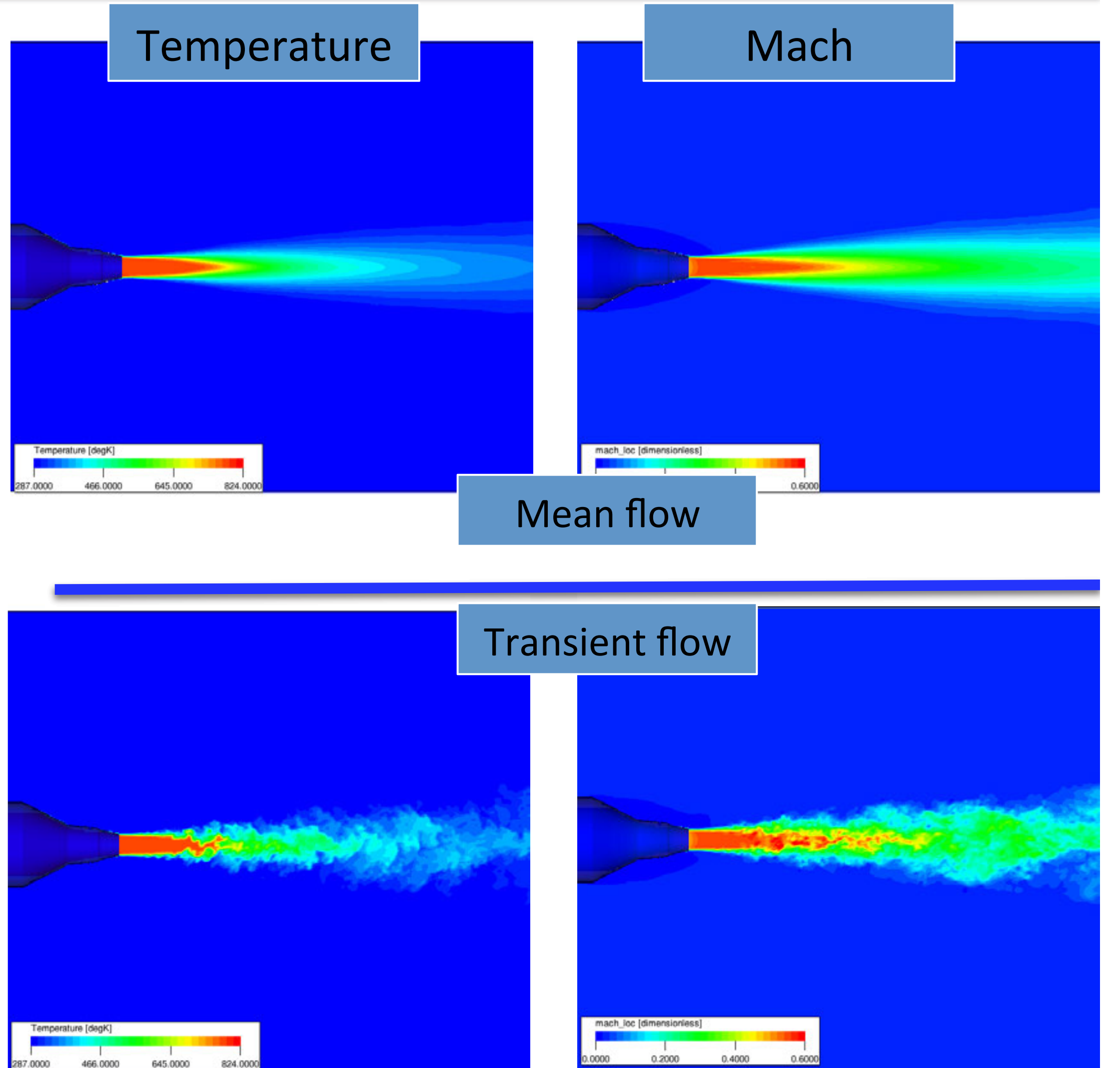
Applications



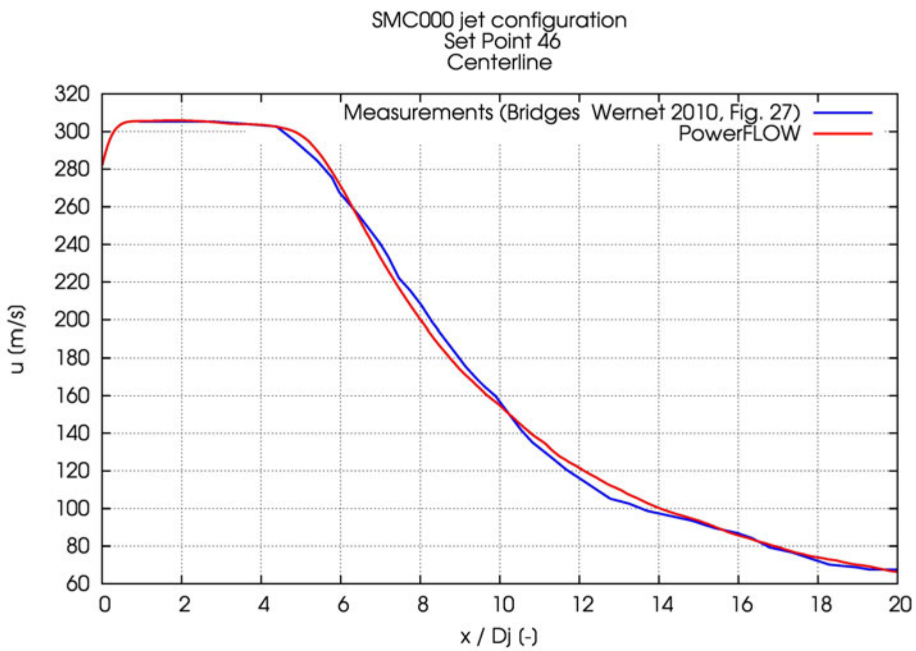
Jet Noise: SMC000 (SP46): Ma=0.9, T_j/T_o=2.7

$M_j = U_j/a_j$	$M_a = U_j/a_{inf}$	T_j/T_{inf}
0.548	0.90	2.70

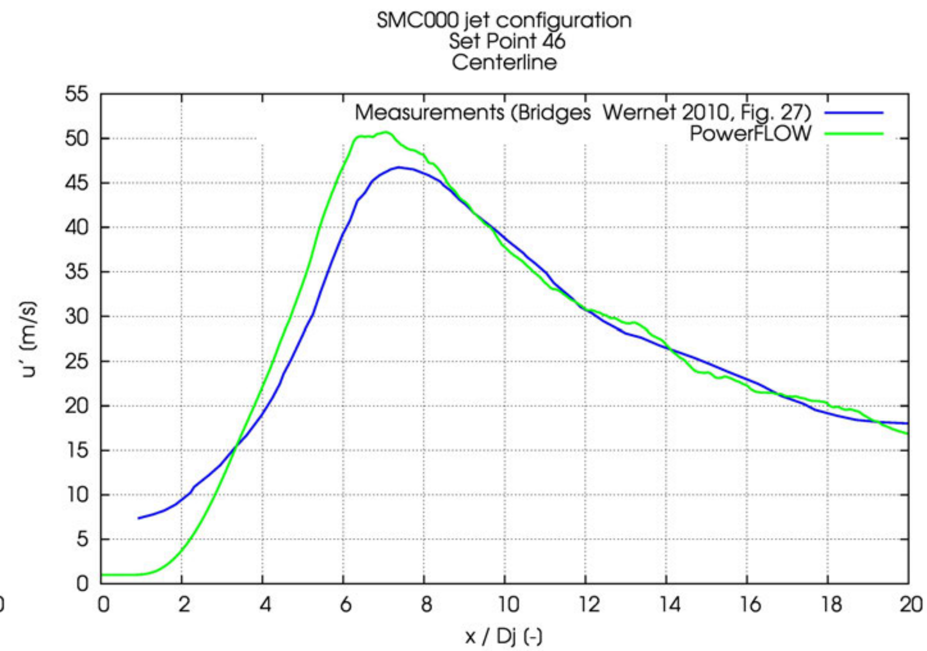




3D SMC Jet, SP46: Centerline mean and RMS velocity

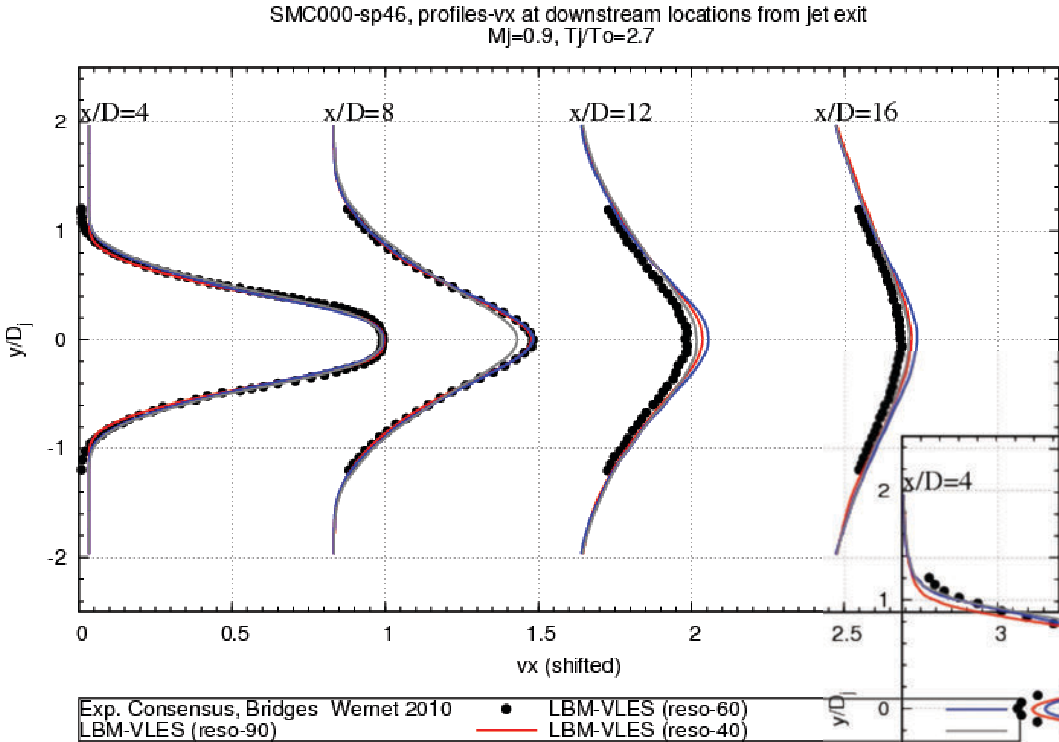


Mean velocity

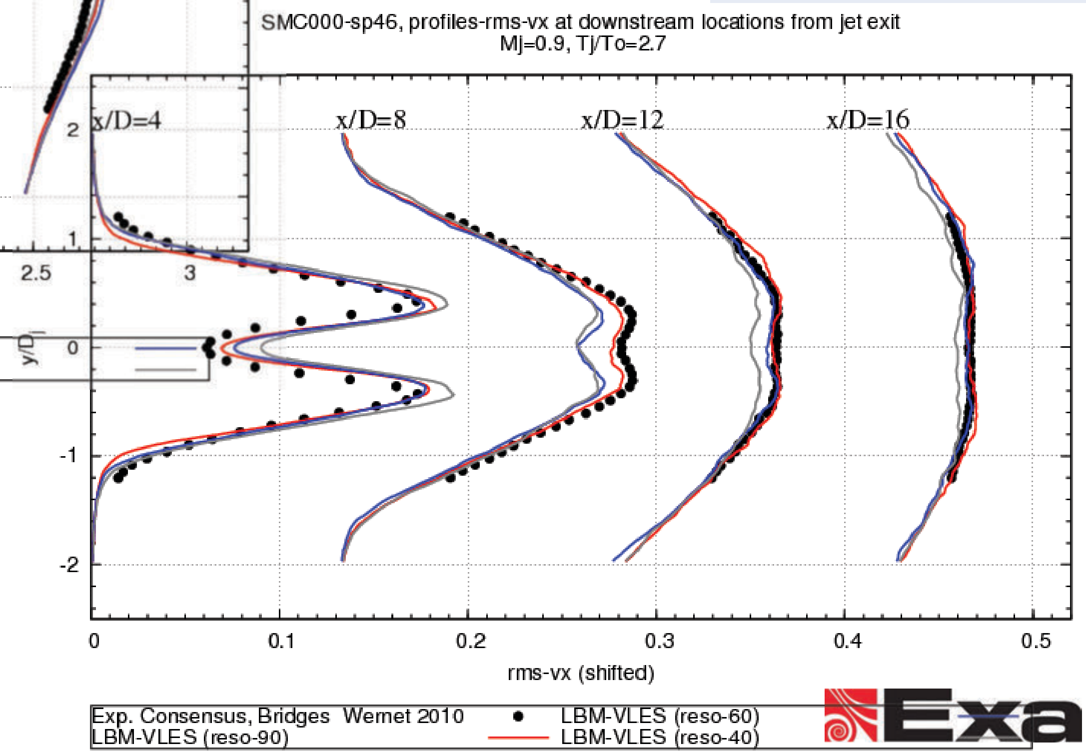


RMS velocity

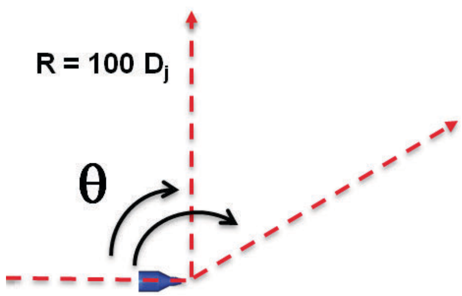
3D SMC Jet, SP46: Radical profiles of mean and RMS velocity

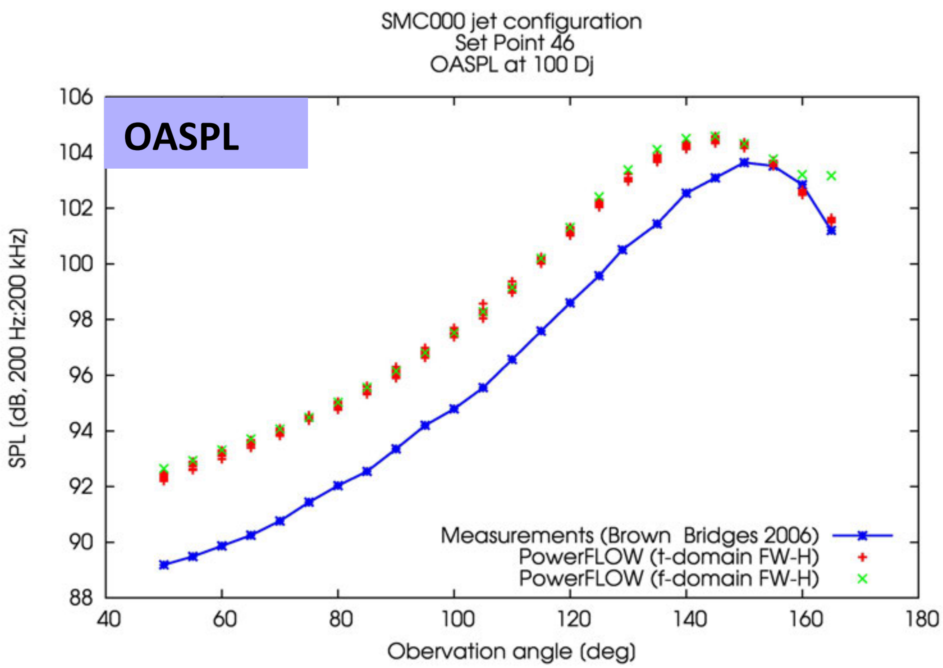


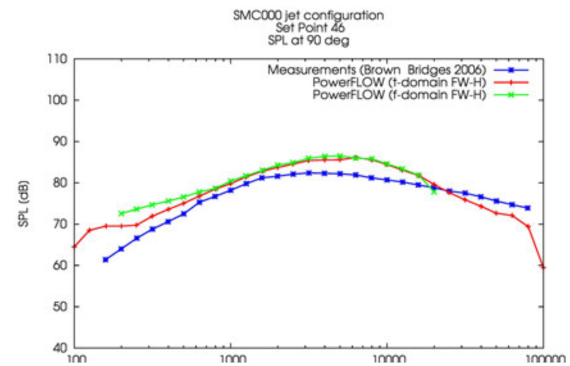
Exp.
Reso-90
Reso-60
Reso-40



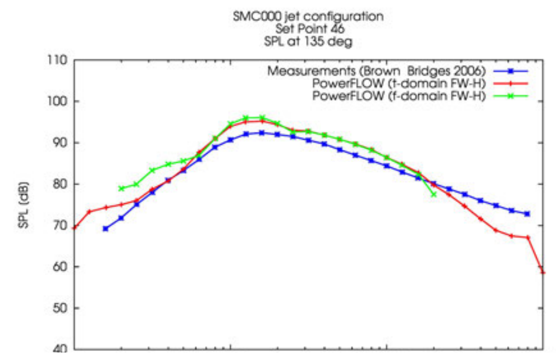
3D SMC Jet, SP46, FW-H OASPL and Far-field probes



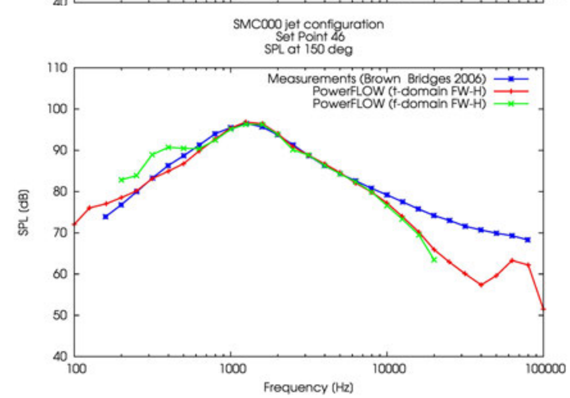




90º

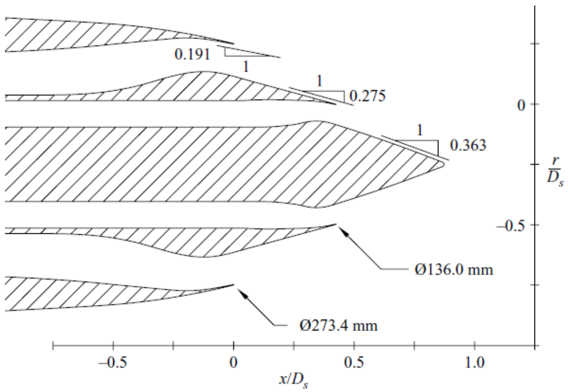


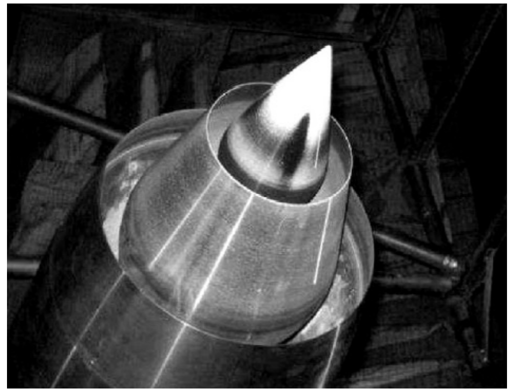
135º

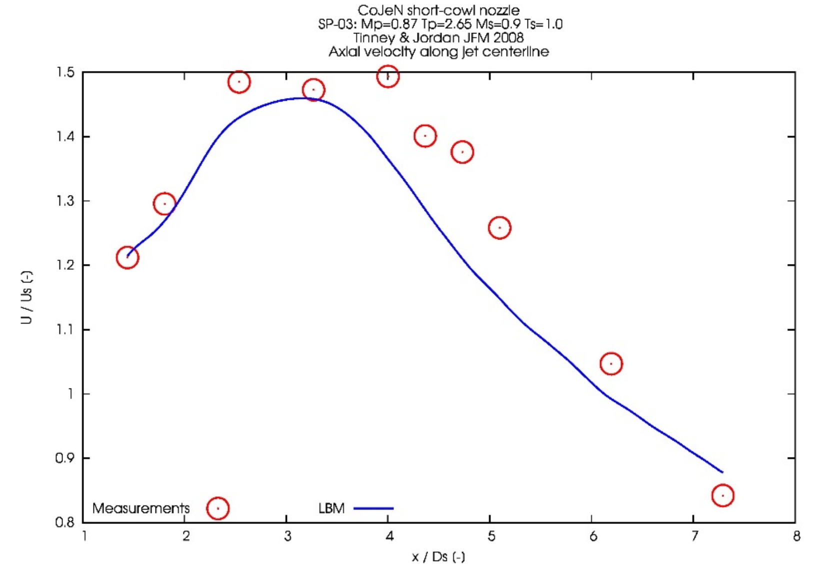


150º

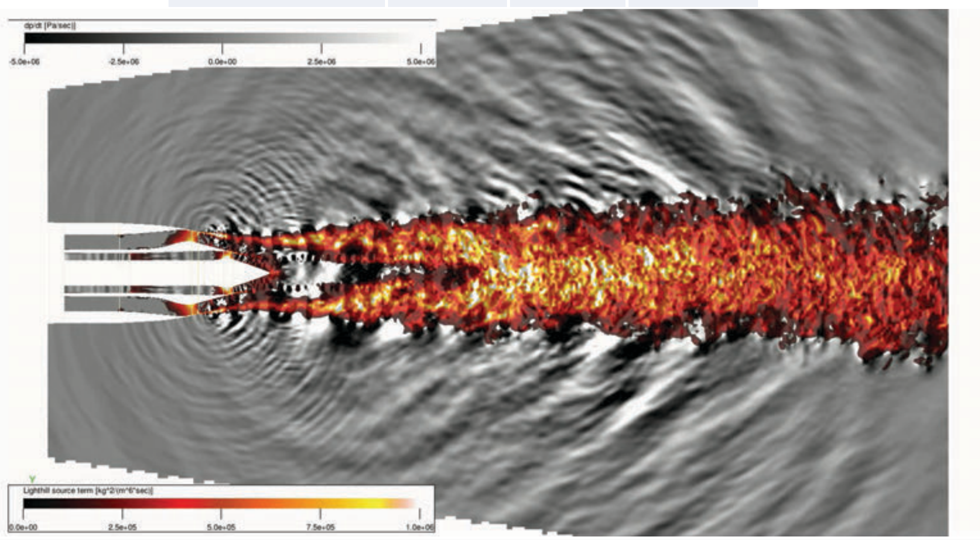
Co-axial Nozzle case

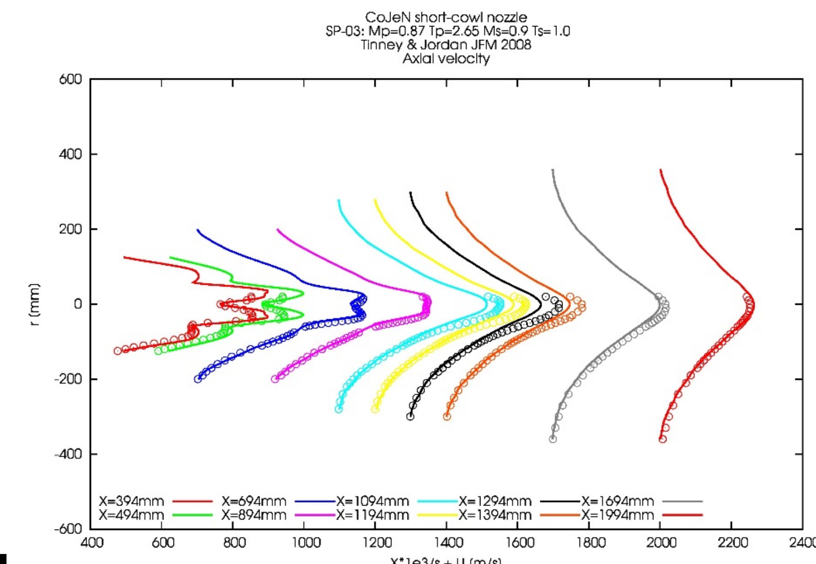






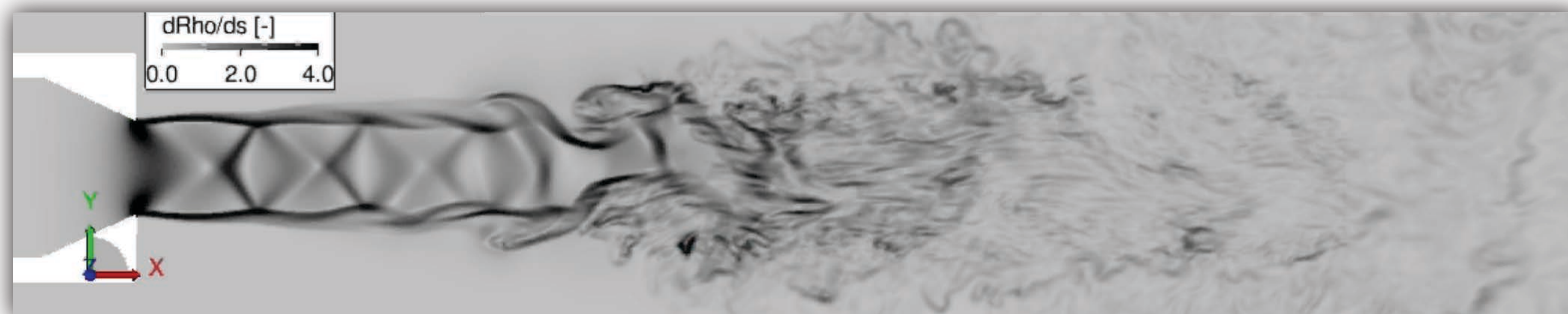
jet	M	Ma	Tr
primary	0.87	1.41	2.65
secondary	0.90	0.90	1.0



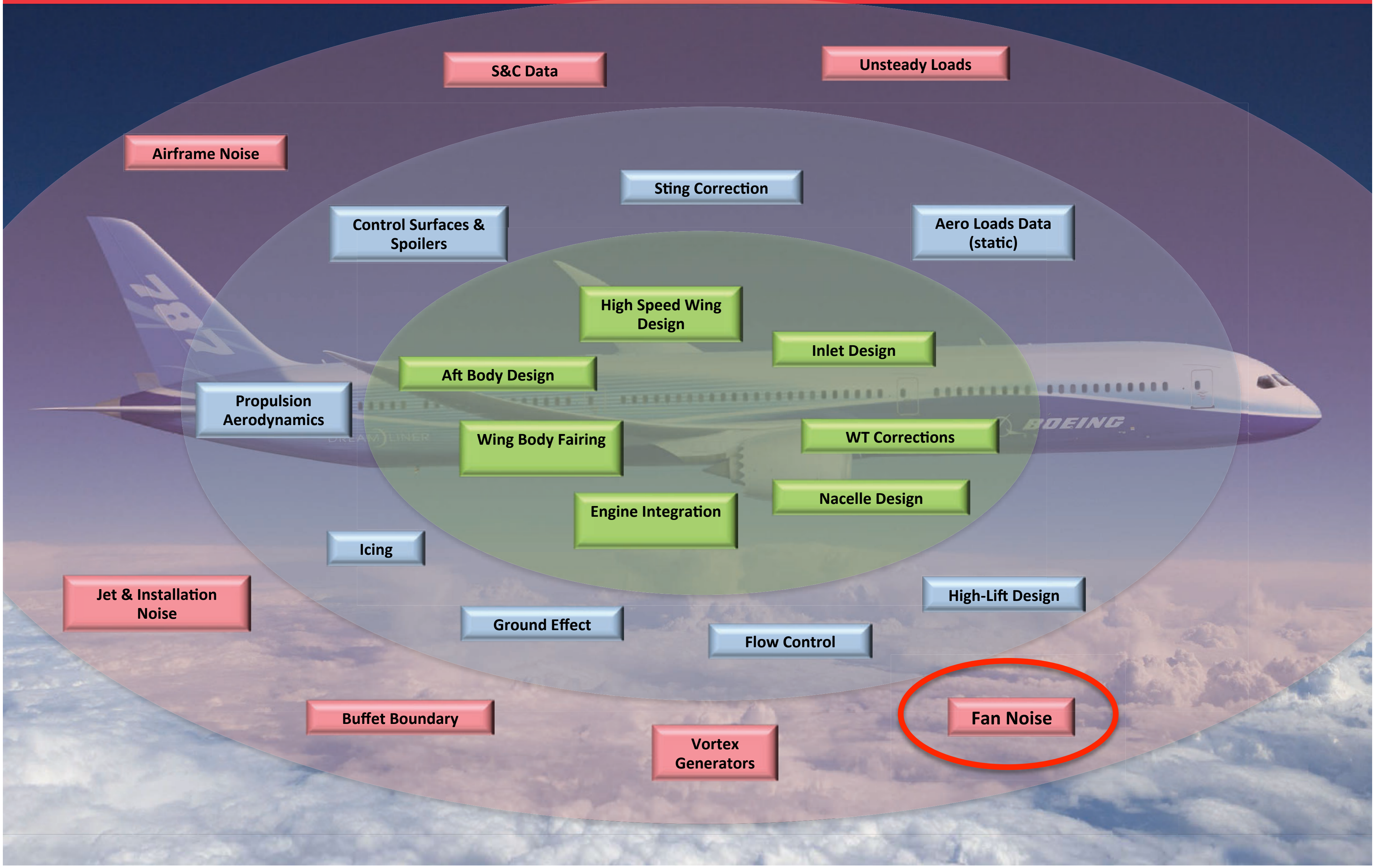


Tinney & Jordan, JFM 611, 2008 – co-axial subsonic jets

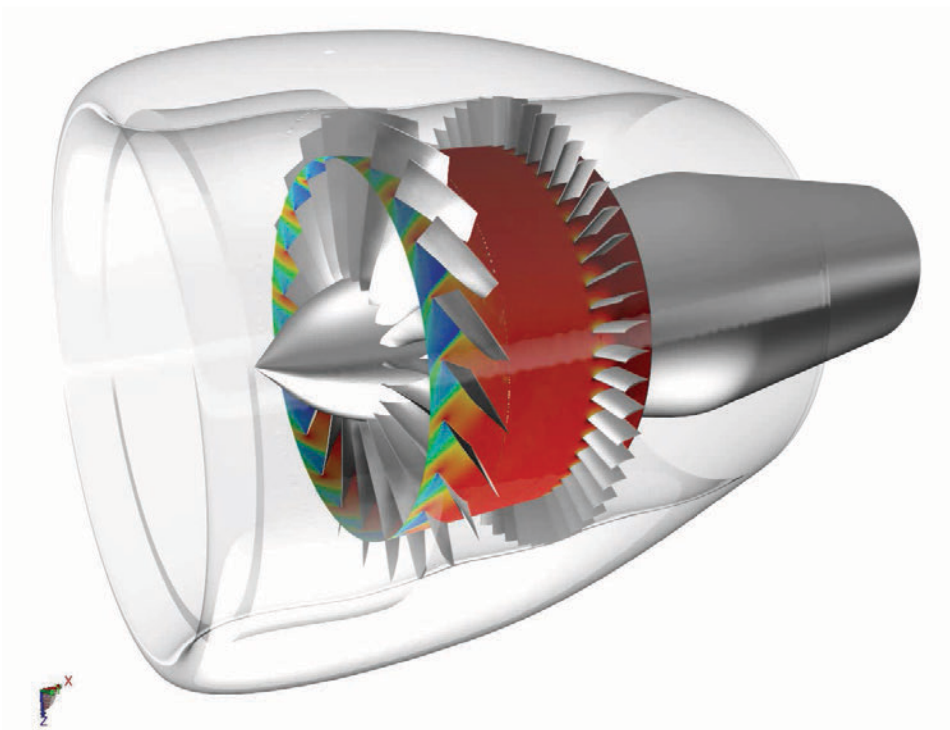
Supersonic Jets (Work in Progress)

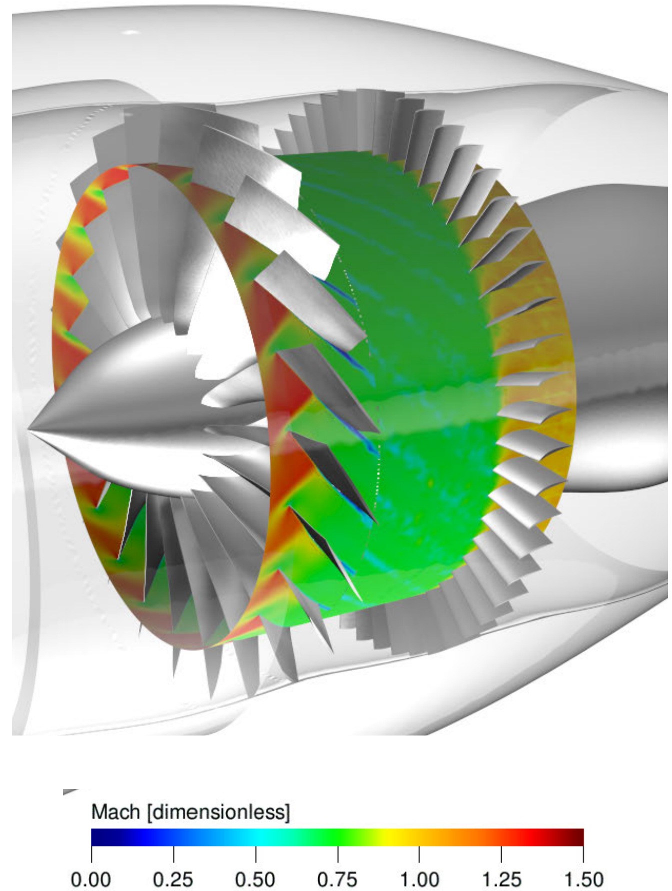


Applications



RC2 Case @12567 rpm

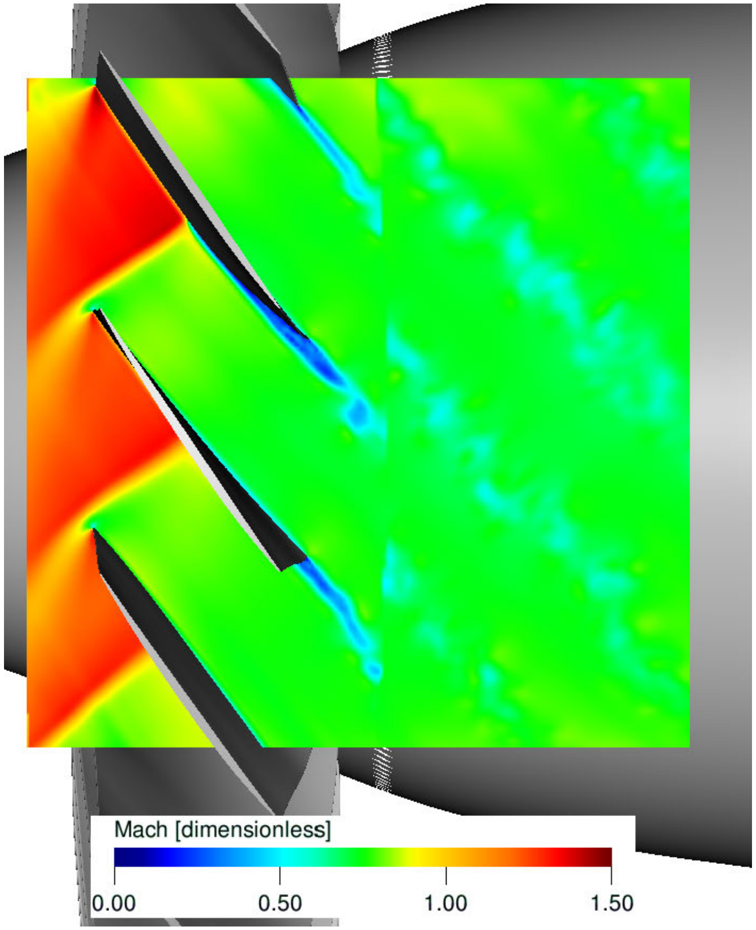




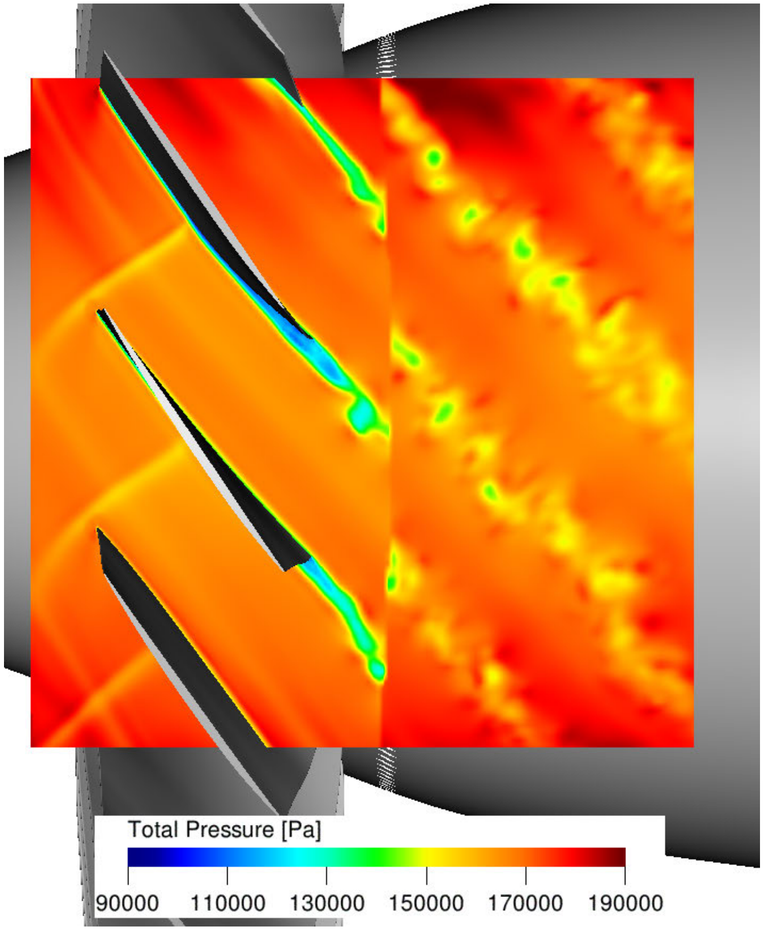
Density on rotor suction side

Flow analysis: slice @ r/R=0.8

Relative Mach number

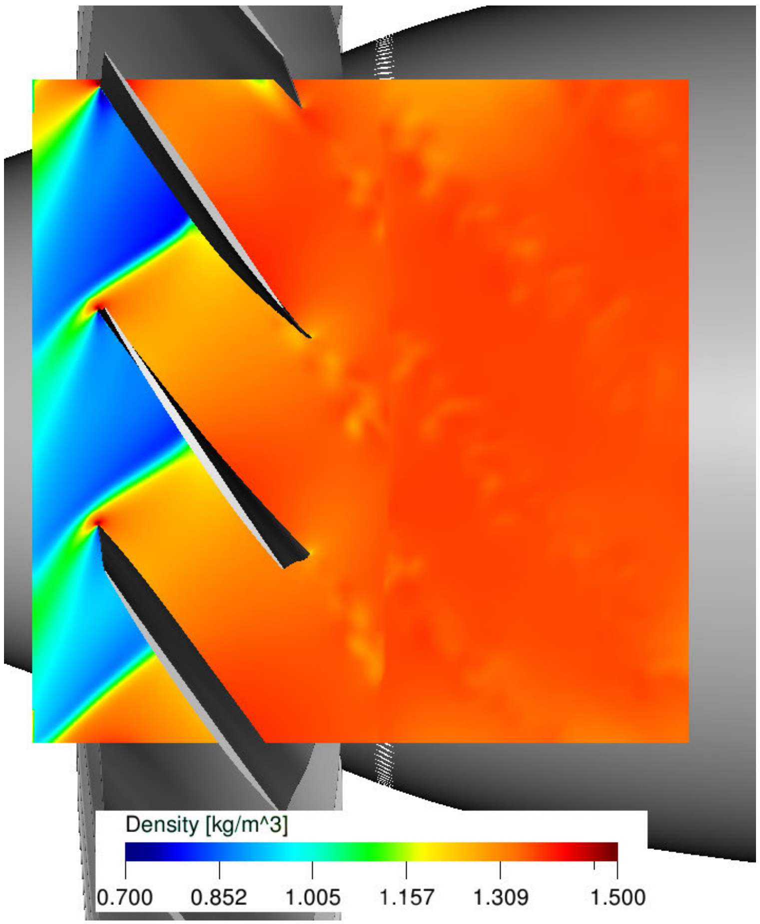


Total Pressure



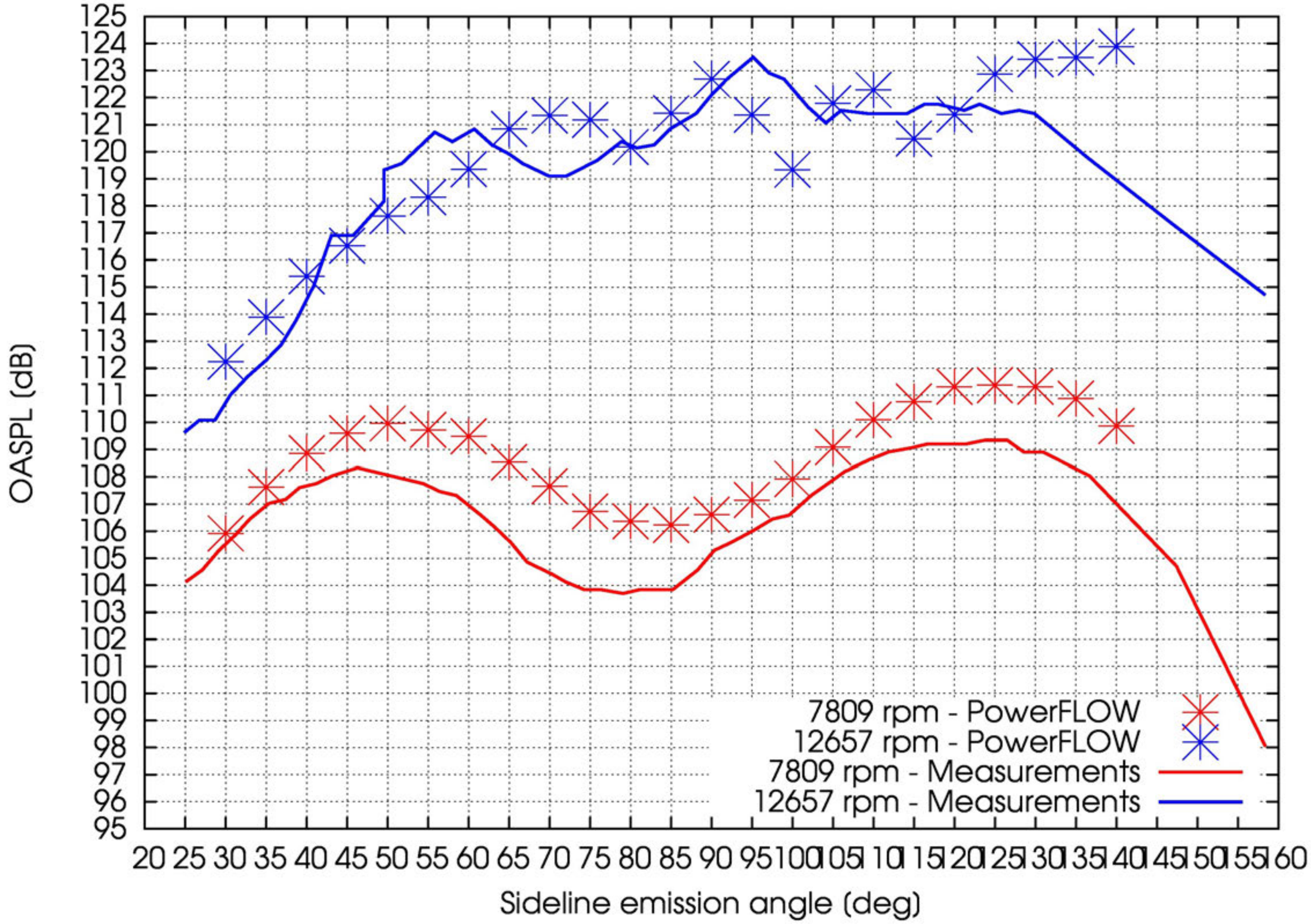
Flow analysis: slice @ r/R=0.8

Density



Density Gradient

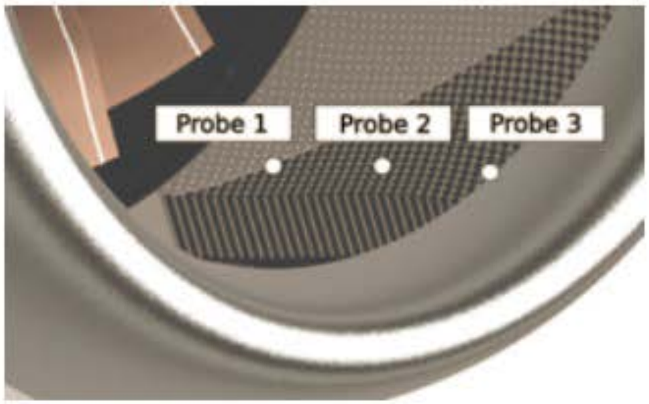
Far-field noise results

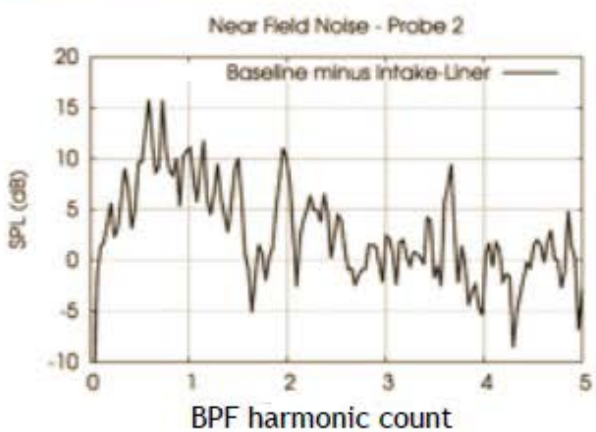


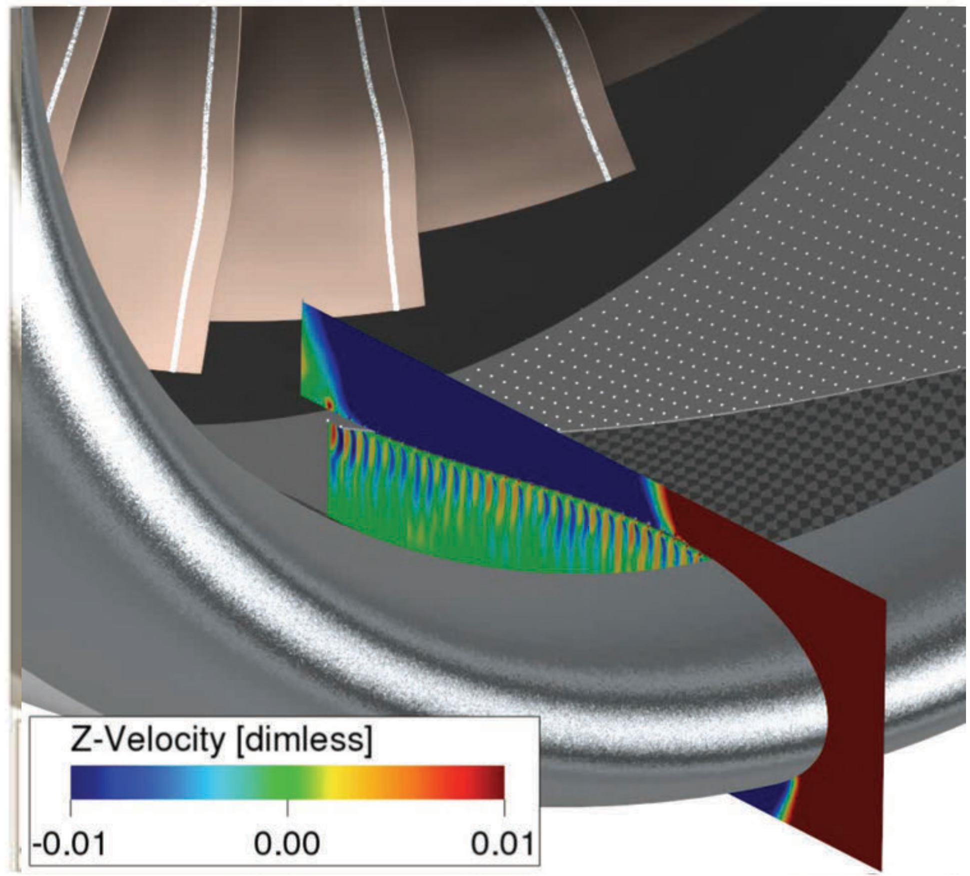
Exa

Liner Simulation - Preview

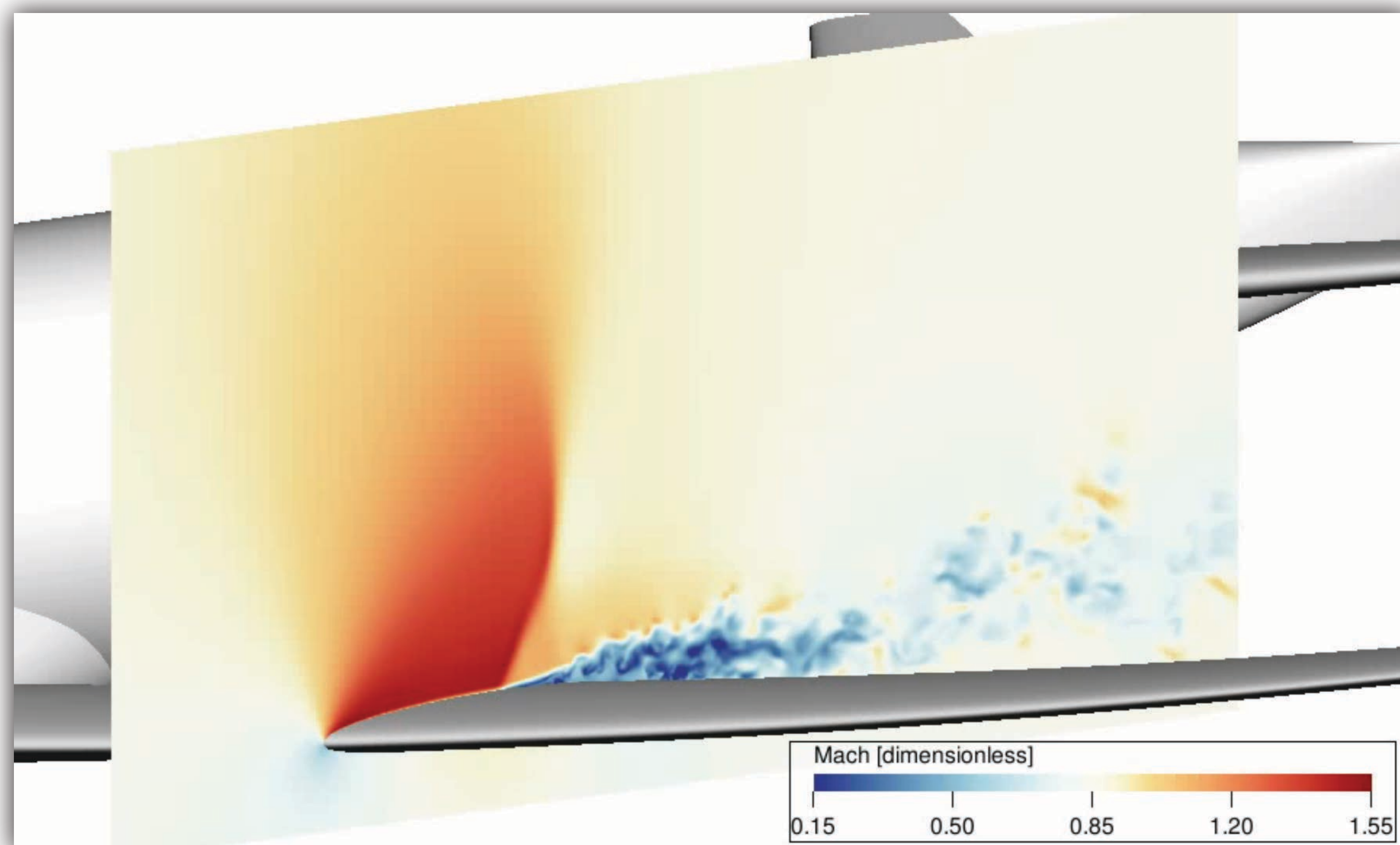
- 1 DoF honeycomb liner
- Realistic orifice diameter, face sheet thickness and porosity (> 8000 orifices and honeycomb cells)
- Optimal design for BPF-2 and ~BPF-4
- Expected broadband properties because of slightly variable depth





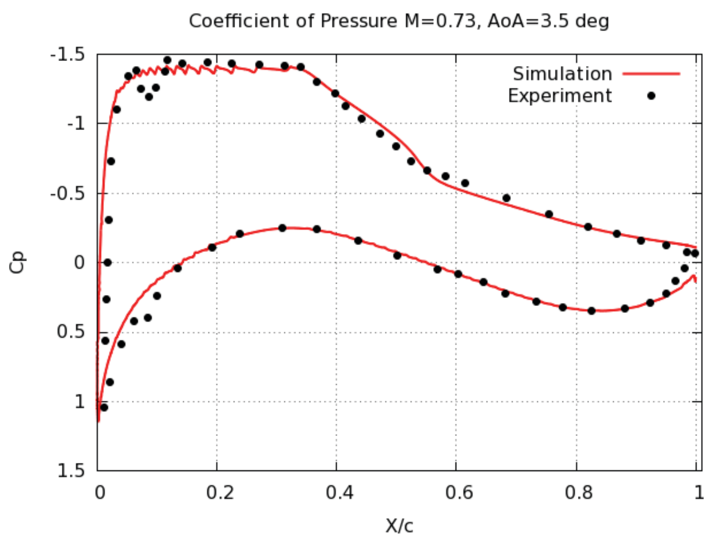


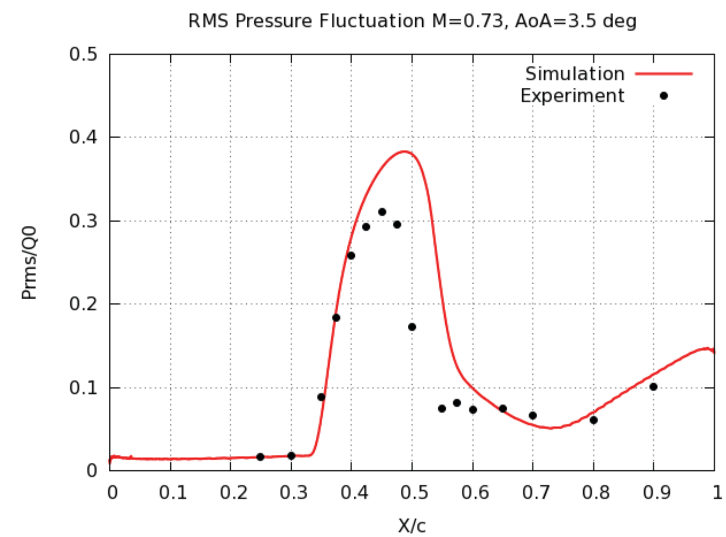
Outlook: High-Speed Buffet



Transonic/Buffeting (Preliminary)

- Buffeting study on OAT15A Supercritical Airfoil
  - *Shock wave- boundary layer interaction involving large scale instabilities.*
  - *Preliminary 2D simulation at M= 0.73, angle of attack= 3.5^{o}, Re≈ 3e6*



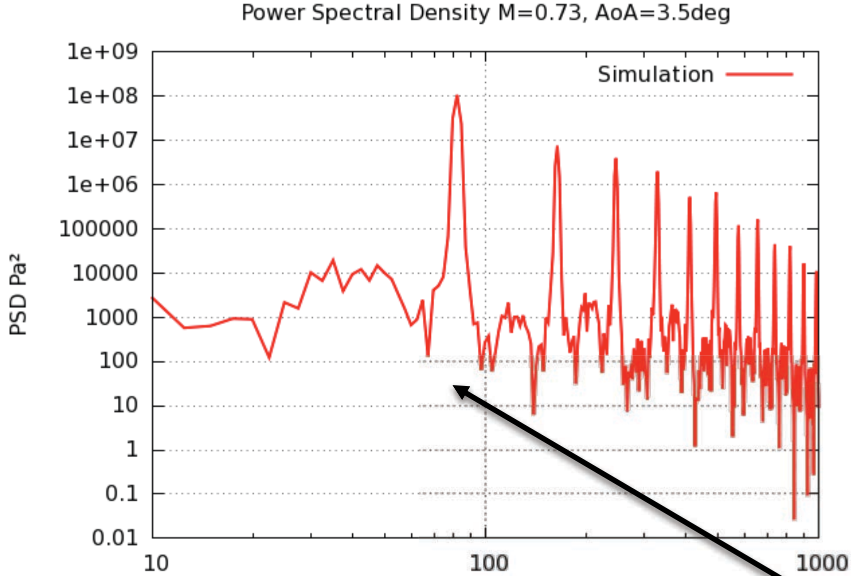


  - *Close agreement of average coefficient of pressure over the surface and amplitude of oscillation with experiments*.*

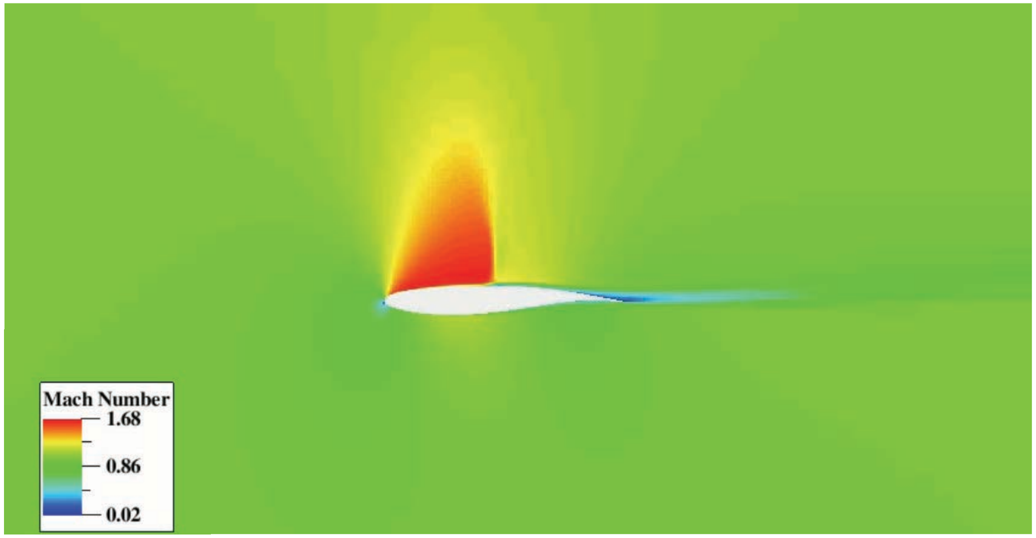
***Reference**: Jacquin L., Molton P., Deck S., Maury B., Soulevant D., 'An Experimental Study of Shock Oscillation over a Transonic Supercritical Profile', AIAA Journal Vol 47, No 9, 2009.

Transonic/Buffeting (Preliminary)

- Buffeting study on OAT15A Supercritical Airfoil (2D)



Pressure power spectrum of surface signal 45% chord length

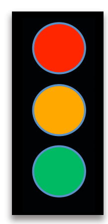


Mach number field

*Frequency of oscillation (experiments): **78 Hz***
*Obtained frequency: **82 Hz***

Summary

- Extension of LBM to transonic & supersonic flows
  - *Achieved through hybrid higher-order LBM scheme*
  - *Enables simulations up to ~Mach 2.0*
  - *Preserves all key advantages of low speed LBM versions*
- Main Initial Application Targets
  - *Unsteady high-speed aerodynamics (buffet, …)*
  - *Flow control*
  - *Propulsion noise: fan, jet & installation noise*
- Status of LBM with regard to CFD Vision 2030 Report
  - *Efficient handling of unsteady turbulent flows with significant regions of separation*
  - *Mesh generation*
  - *Robustness and automation of CFD simulations*
  - *Efficient use of HPC infrastructure*
  - *Managing very large amounts of data*
  - *Multi-disciplinary analysis & optimization*



No significant progress yet
Work in progress
Achieved

Thank You!