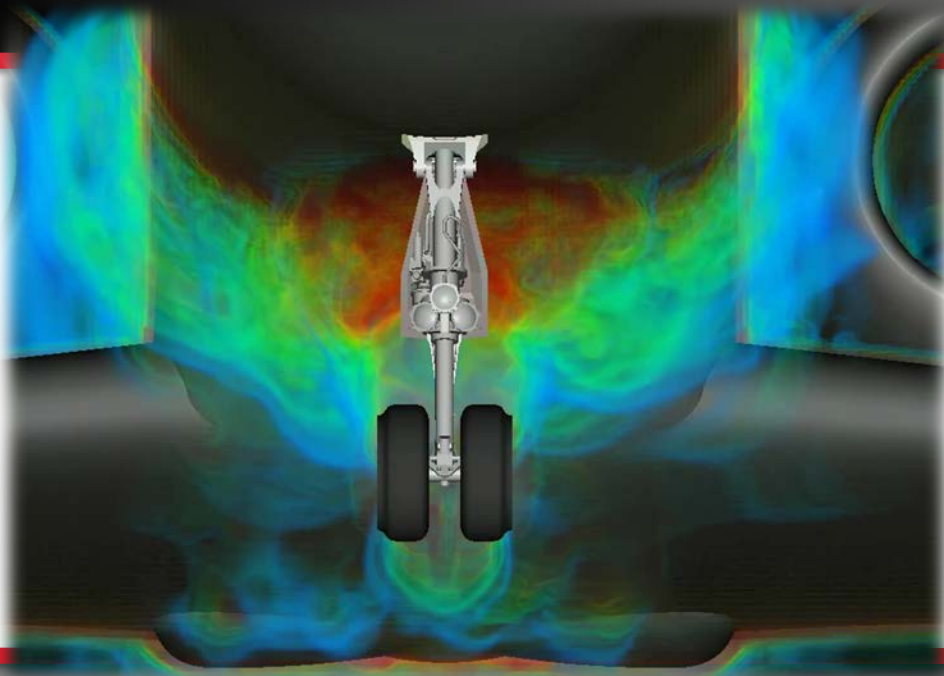


The Lattice-Boltzmann Method

An alternative for unsteady flow simulations

Swen Noelting, Managing Director Aerospace
Ehab Fares, Technical Manager, Aerospace Applications

Conference on Future Directions in CFD Research
Hampton, August 6-8, 2012

© Exa Corporation Confidential

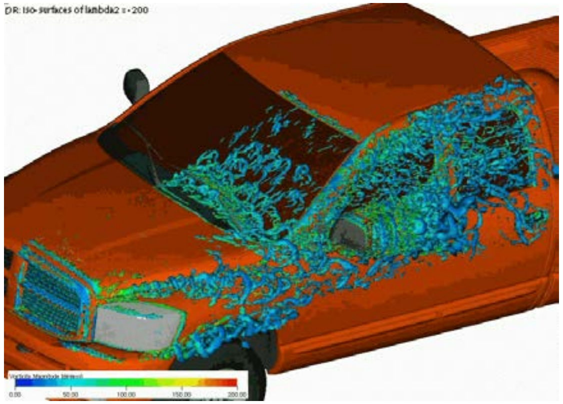
Overview

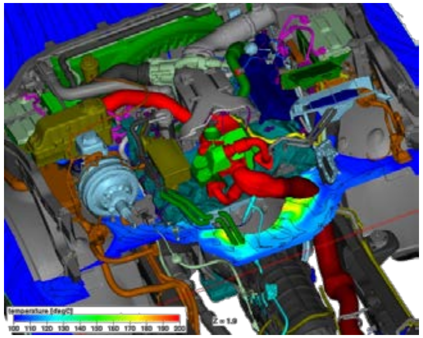
- Exa Corporation Overview
- Lattice Boltzmann Method
- Aerospace Applications
- Challenges & Plans

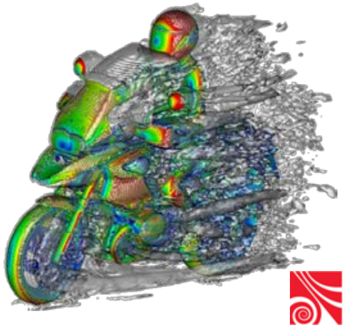
© Exa Corporation Confidential

Exa Corporation Overview

- Founded in 1992
  - *Based on research at MIT*
  - *IPO in June 2012*
  - *Total investment in LBM technlogy > $200M*
- Focus on vertical markets
  - *Initial market: ground transportation*
  - *Built strong industrial partnerships*
- Targeted expansion to Aerospace in past 5 years







Exa

© Exa Corporation Confidential

Automotive Example

© Exa Corporation Confidential

Overview

- Exa Corporation Overview
- Lattice Boltzmann Method
- Aerospace Applications
- Challenges & Plans

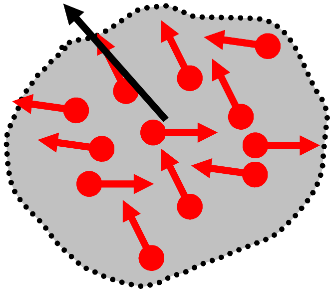
© Exa Corporation Confidential

Lattice Boltzmann Method

More General, Simpler Physics

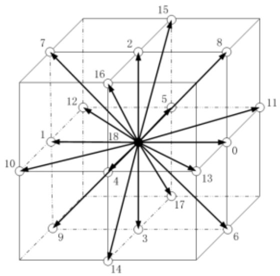
Microscopic
- Molecular Dynamics

Boltzmann Equation



Mesoscopic
- Discrete Particle Dynamics

Lattice Boltzmann



Macroscopic
- Continuum Equation

Navier-Stokes

© Exa Corporation Confidential

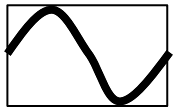
LBM Key Characteristics

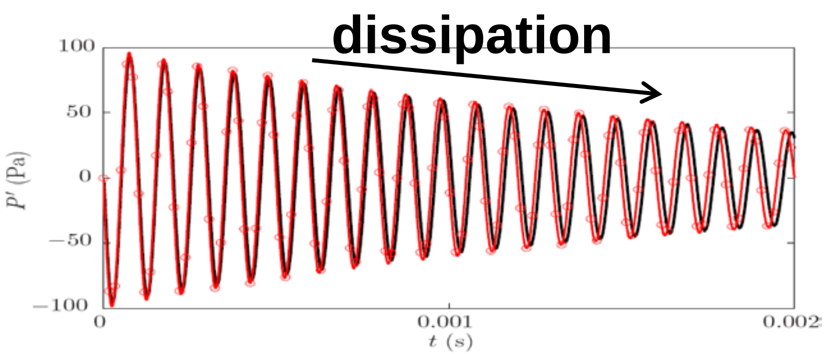
- Navier-Stokes physics are fully recovered
- Highly efficient unsteady flow solver
- Very low numerical dissipation

© Exa Corporation Confidential

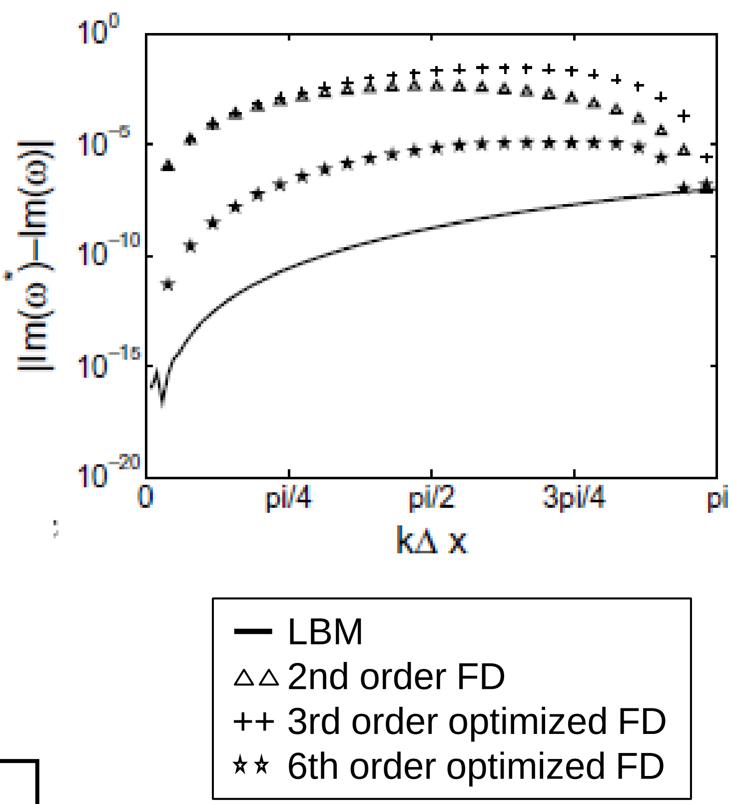
Comparison to higher-order NS Schemes

- Standing planar wave





Dissipation Error



Marié S., Ricot D., Sagaut P. “Comparison between lattice Boltzmann method and high order Navier Stokes schemes for computational aeroacoustics”, Journal of Computational Physics 228, 2009, p. 1056 – 1070.

© Exa Corporation Confidential

LBM Key Characteristics

- Navier-Stokes physics are fully recovered
- Highly efficient unsteady flow solver
- Very low numerical dissipation
- Easy handling of very complex geometries
  - *Automatic generation of volume mesh*
  - *Nested cartesion mesh with multiple resolution level*

© Exa Corporation Confidential

Process Flow Chart

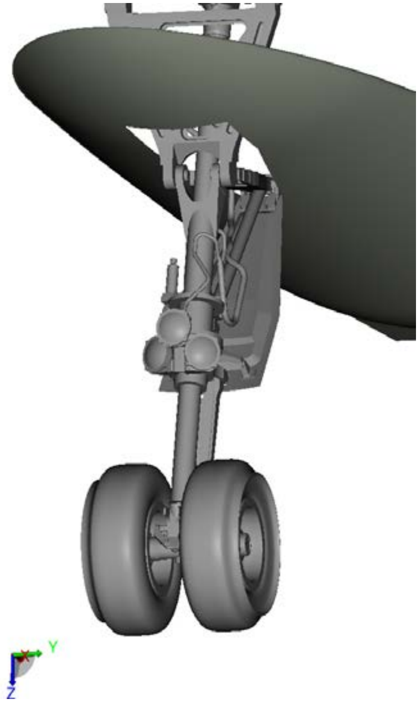
Engineer

- CAD geometry
- Surface mesh — ~6 hours
- Case setup (VR setup) — ~3 hours

Compute Cluster

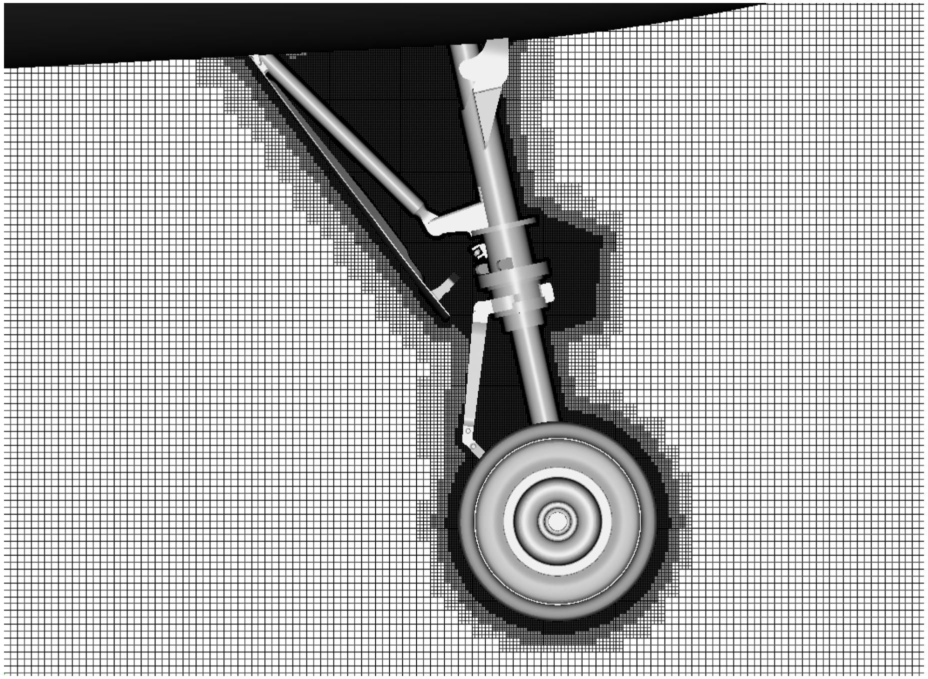
- Automatic volume grid generation — 2 hours
- Simulation — 16 hours on 512 cores

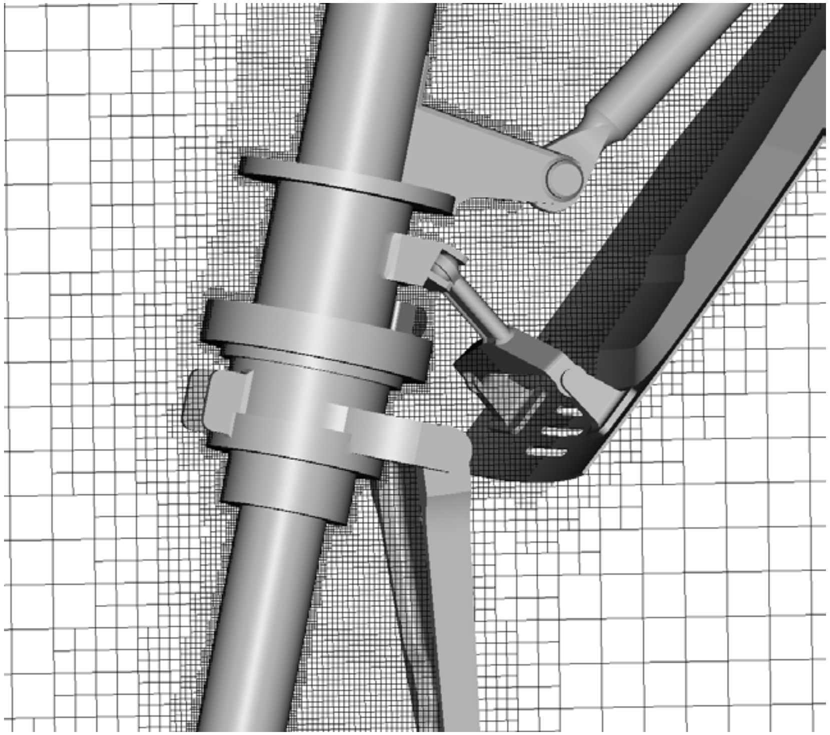
- Post-processing — 4 hours



© Exa Corporation Confidential

PowerFLOW Mesh Structure





© Exa Corporation Confidential

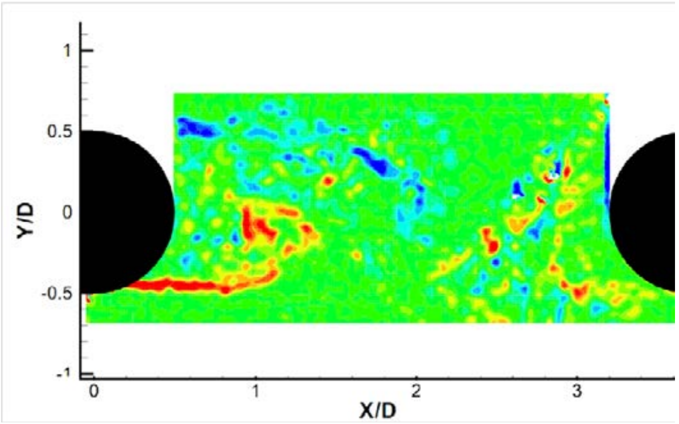
LBM Key Characteristics

- Navier-Stokes physics are fully recovered
- Highly efficient unsteady flow solver
- Very low numerical dissipation
- Easy handling of very complex geometries
  - *Automatic generation of volume mesh*
  - *Nested cartesion mesh with multiple resolution level*
- Stability is a-priori guaranteed
- "LES-like" turbulence model
  - *Modified RNG model in regions of attached/steady flow*
  - *Switch to hyperviscosity-type LES model based on local swirl*
  - *Extended wall model*

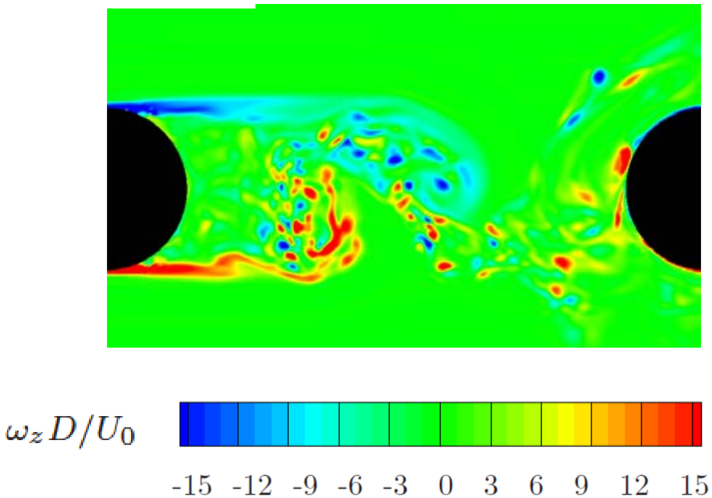
© Exa Corporation Confidential

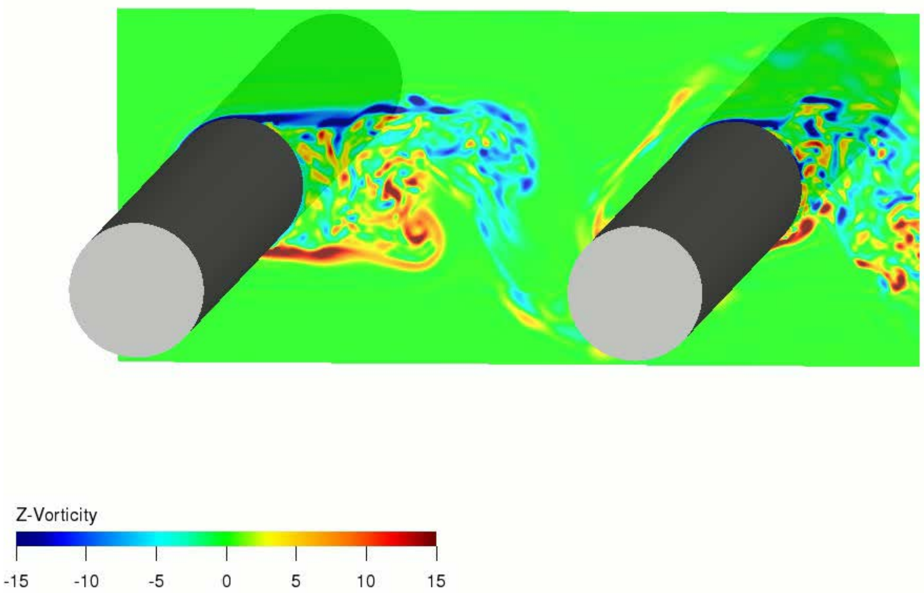
Tandem Cylinders
Instantaneous vorticity field

Experimental PIV (BART)



LBM





© Exa Corporation Confidential

LBM Key Characteristics

- Navier-Stokes physics are fully recovered
- Highly efficient unsteady flow solver
- Very low numerical dissipation
- Easy handling of very complex geometries
  - *Automatic generation of volume mesh*
  - *Nested cartesion mesh with multiple resolution level*
- Stability is a-priori guaranteed
- "LES-like" turbulence model
  - *Modified RNG model in regions of attached/steady flow*
  - *Switch to hyperviscosity-type LES model based on local swirl*
  - *Extended wall model*
- Current version limited to low speed
  - *Update later in this presentation*

Exa

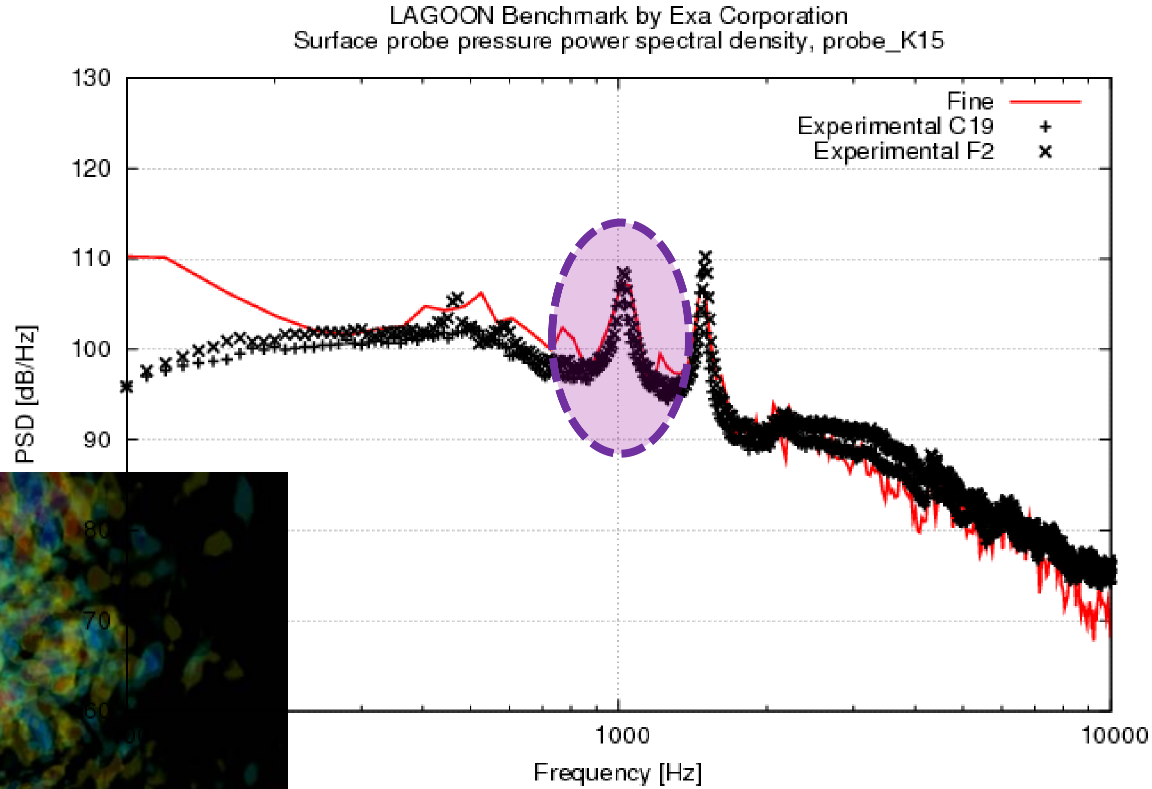
© Exa Corporation Confidential

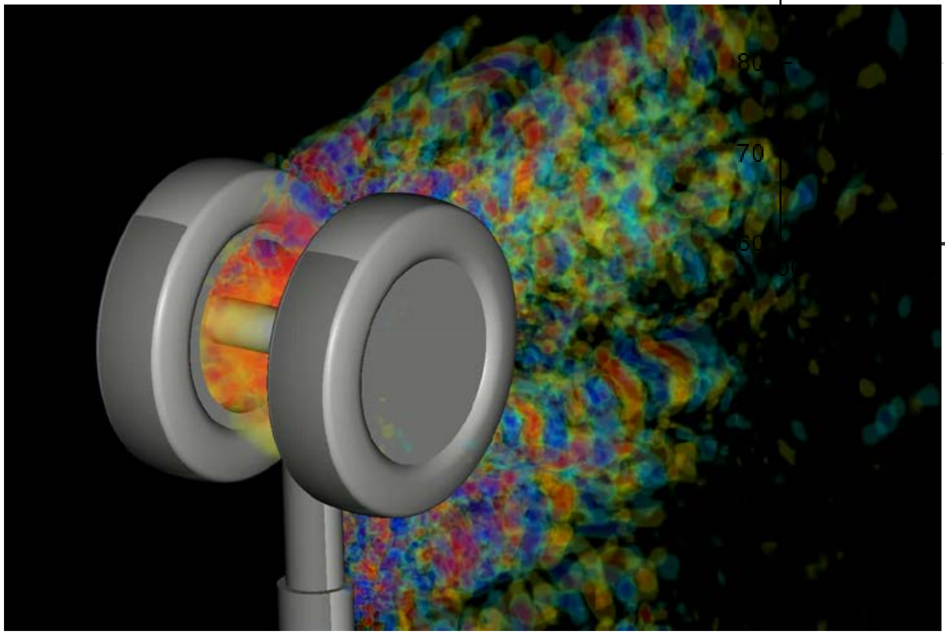
Overview

- Exa Corporation Overview
- Lattice Boltzmann Method
- Aerospace Applications
- Challenges & Plans

© Exa Corporation Confidential

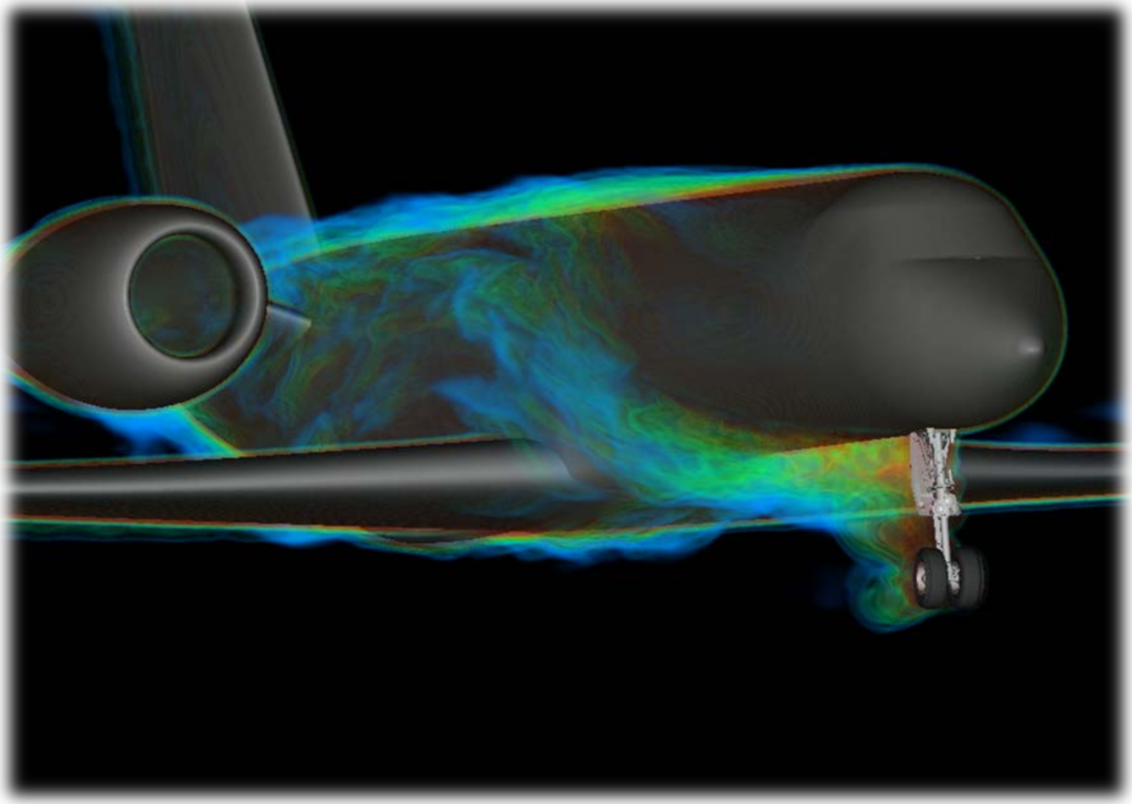
Acoustics – Airframe Noise - LG

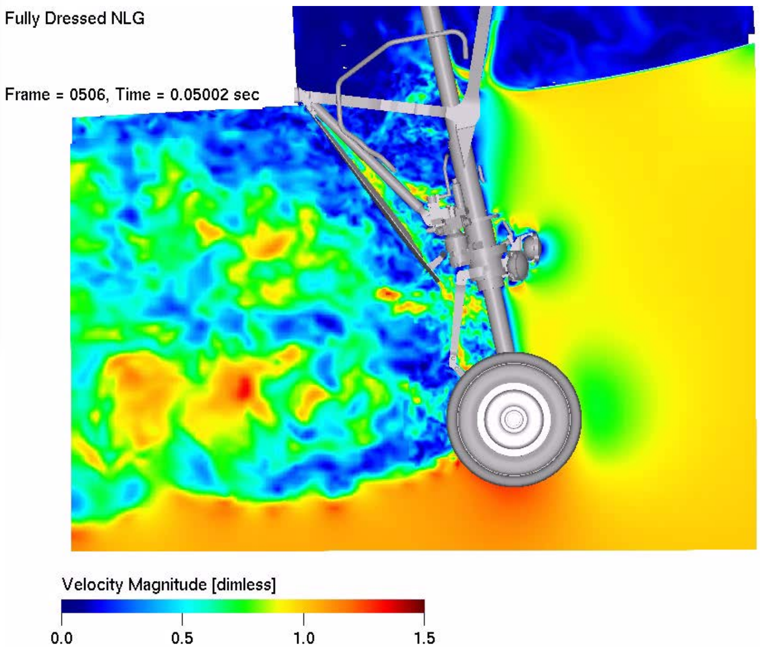




© Exa Corporation Confidential

Airframe Noise:
Full Business Jet with deployed NLG

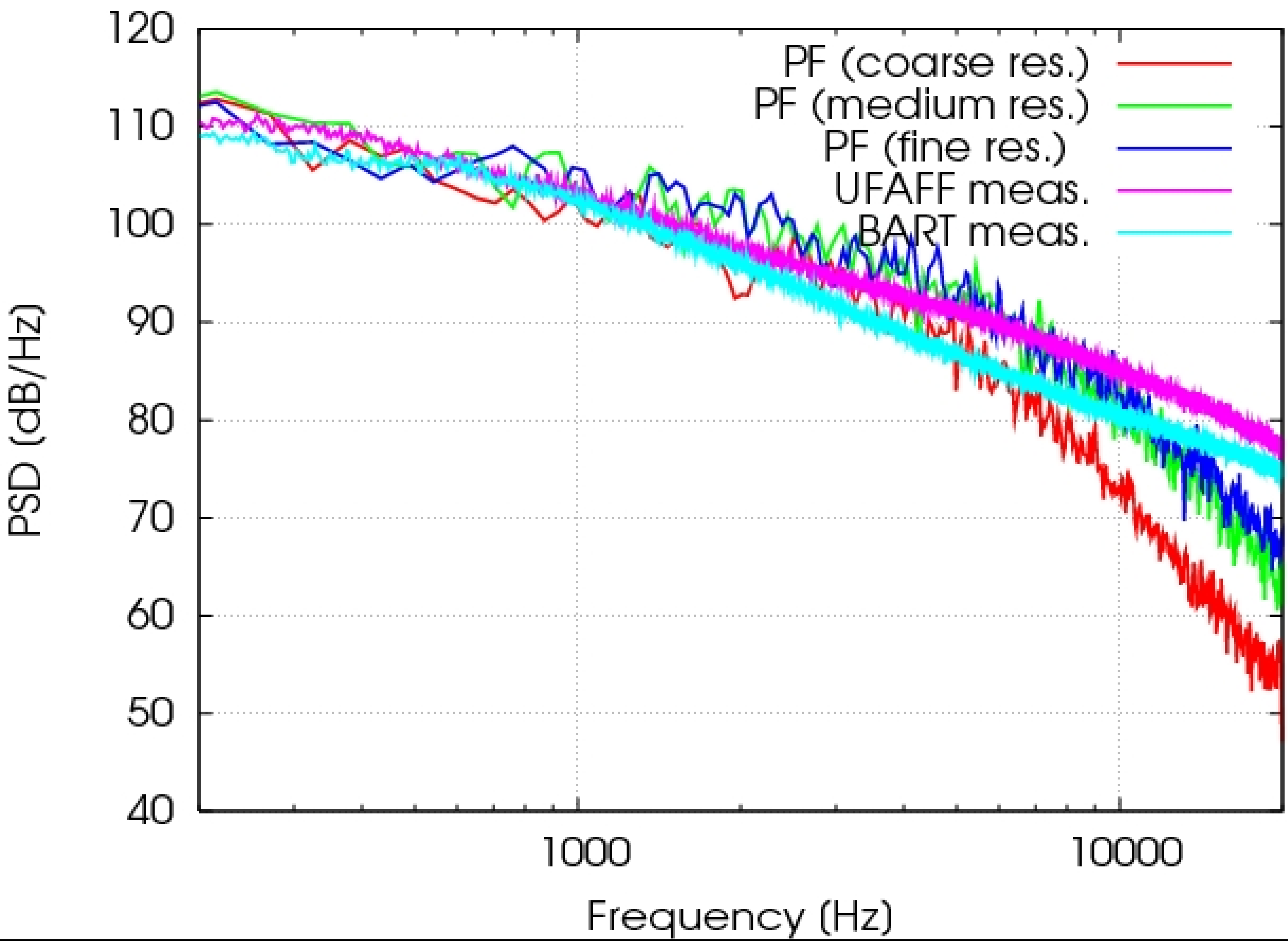


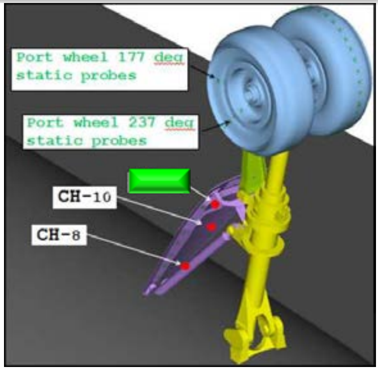


Sources
BANC-II Workshop
AIAA 2012-2235

© Exa Corporation Confidential

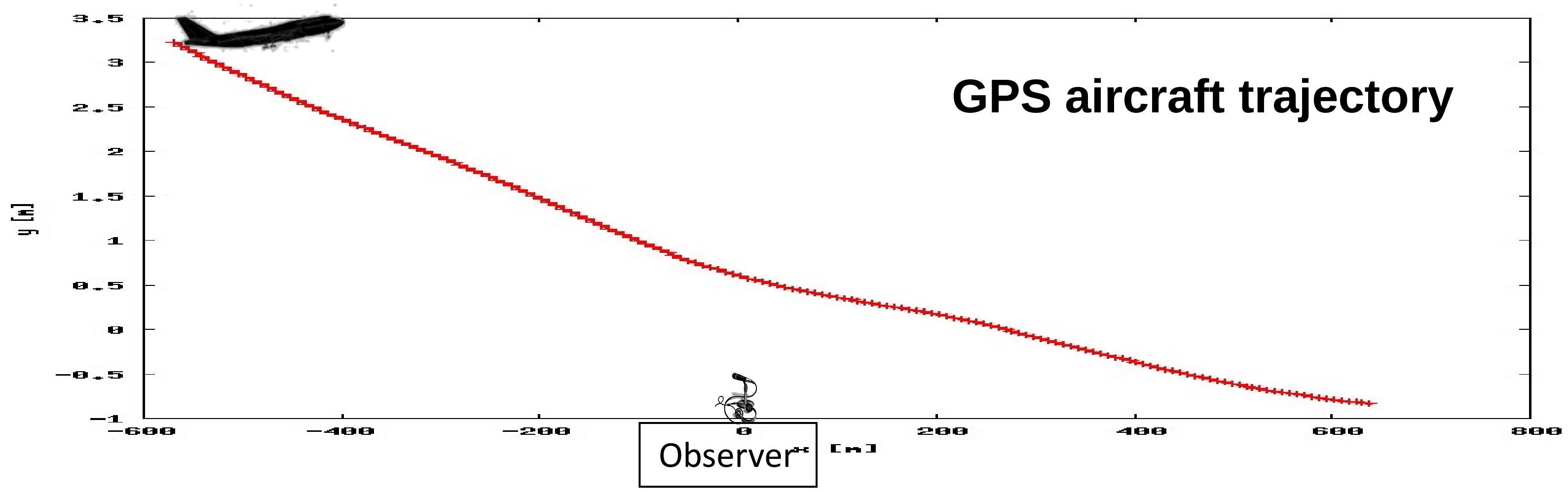
BANC-II/PDCC-NLG: near-field results

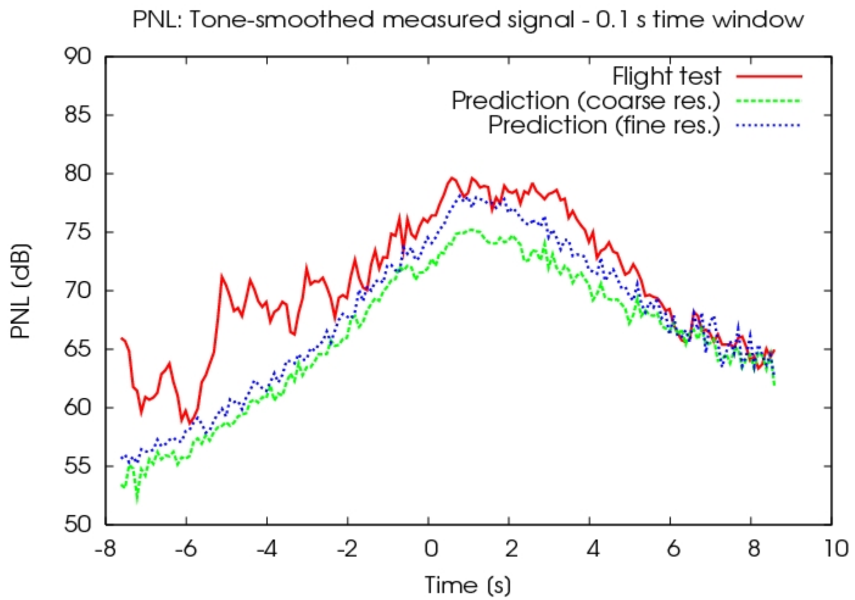




© Exa Corporation Confidential

Towards Virtual Certification

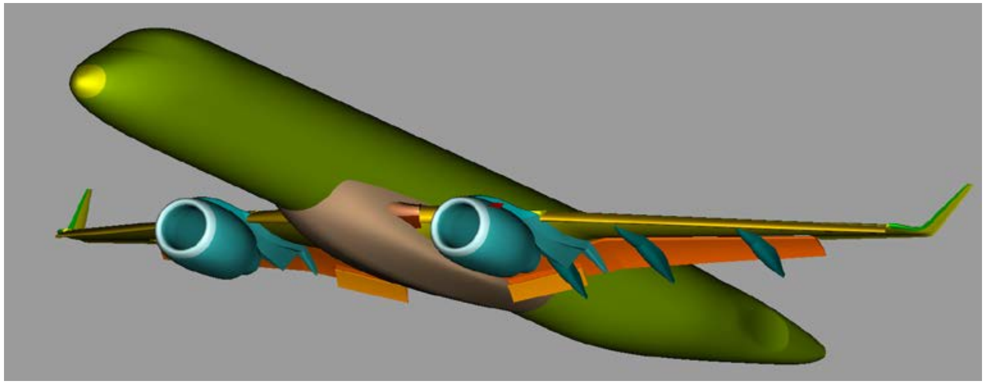


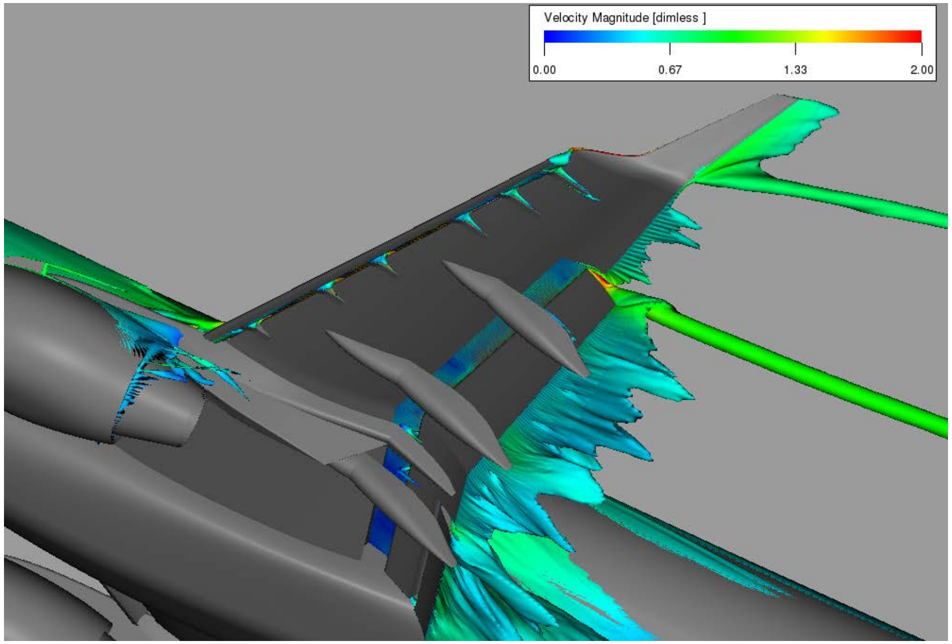


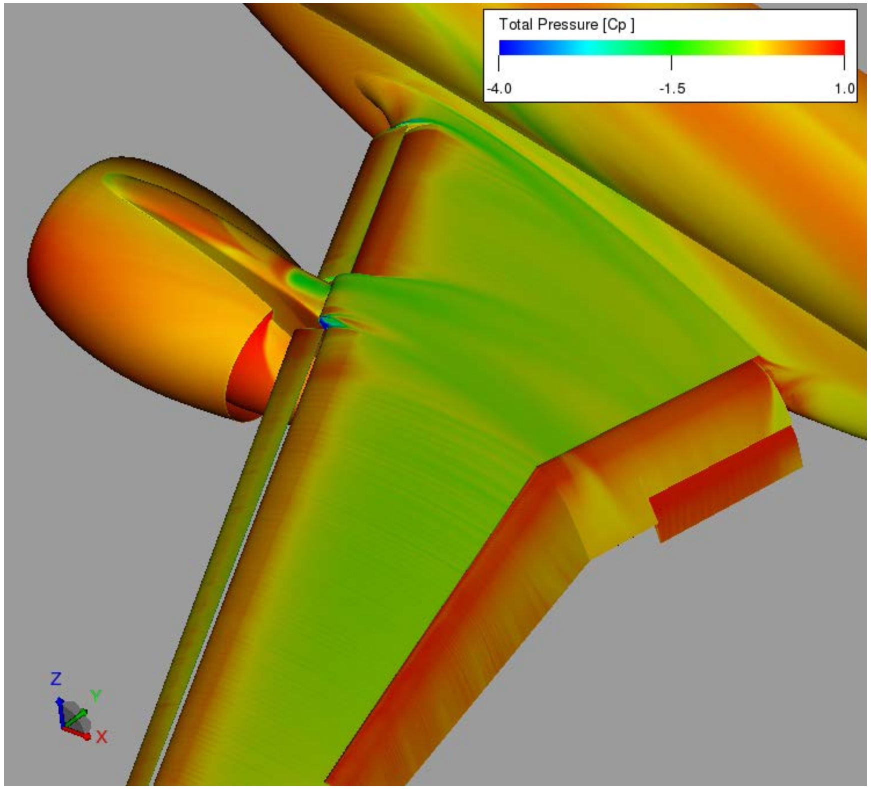
Full on-ground noise signal

© Exa Corporation Confidential

High-Lift Aerodynamics



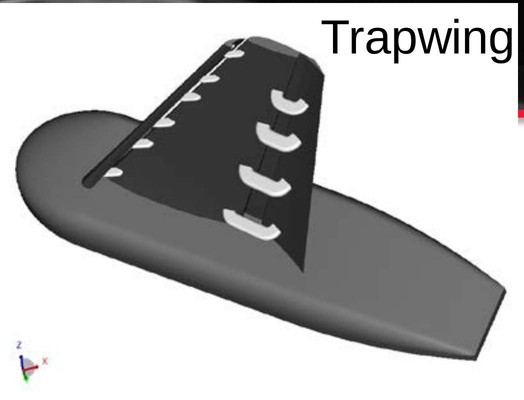


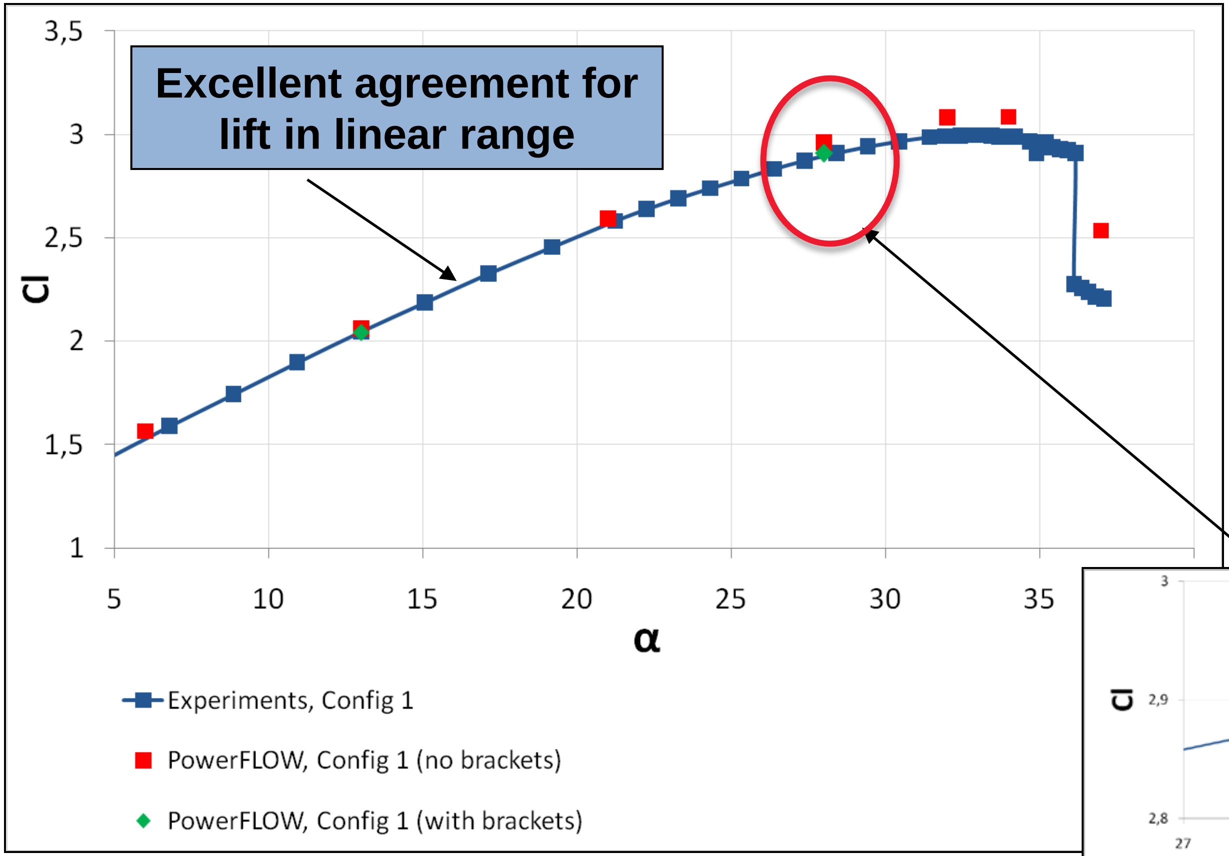


Simplified Geometry

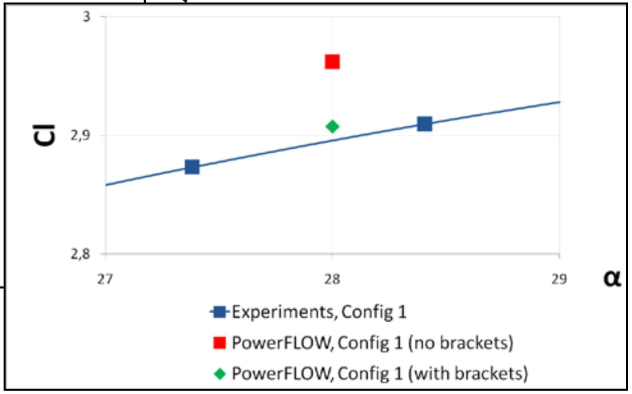
© Exa Corporation Confidential

High-Lift Prediction Workshop





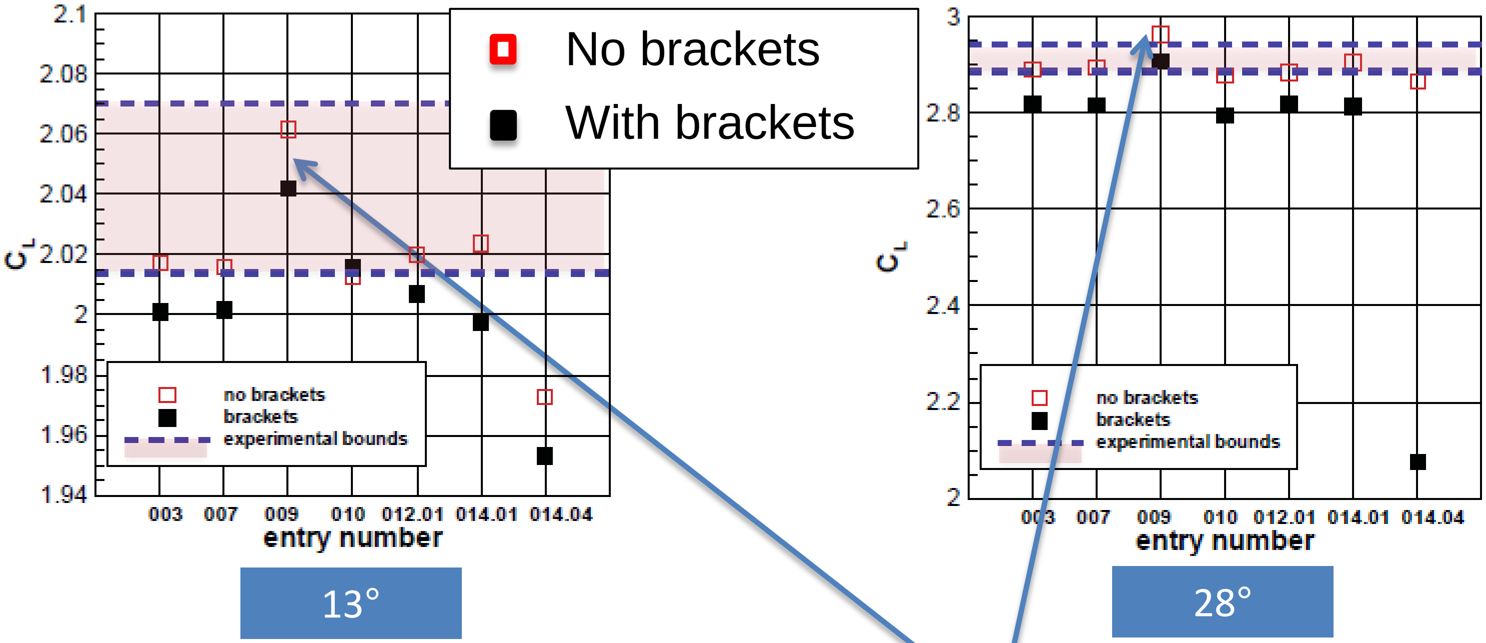
Lift detail at 28º: Excellent prediction for simulation with brackets (as in experiment)



Source: High-Lift Prediction Workshop (Chicago, 2010)

© Exa Corporation Confidential

High-Lift Prediction Workshop: Comparison with other Codes



Source:
Overview Paper
AIAA 2011-939

Entries Numbers:

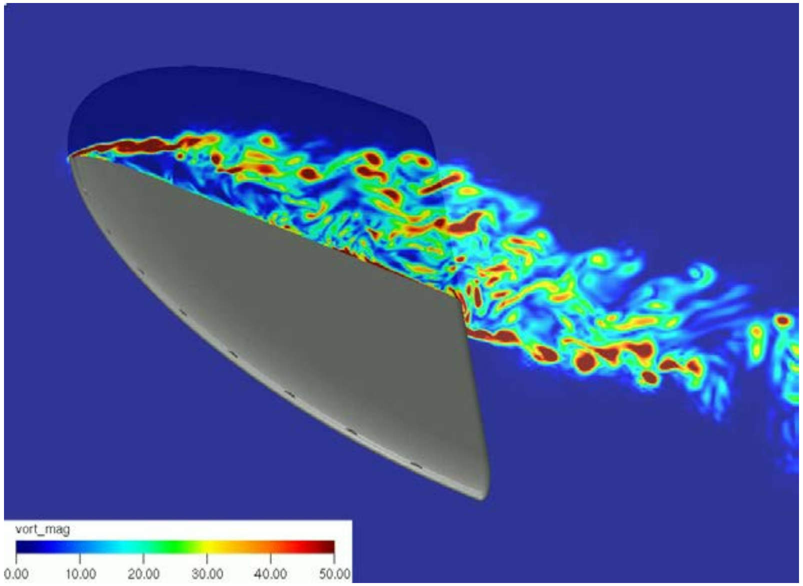
003, 14.01, 14.04:	Overflow (NASA code, used by Boeing)
007	TAU (DLR code, used by Airbus)
009	**PowerFLOW**
010	Edge

LBM predicts lift within experimental bounds
(experiments performed with brackets)

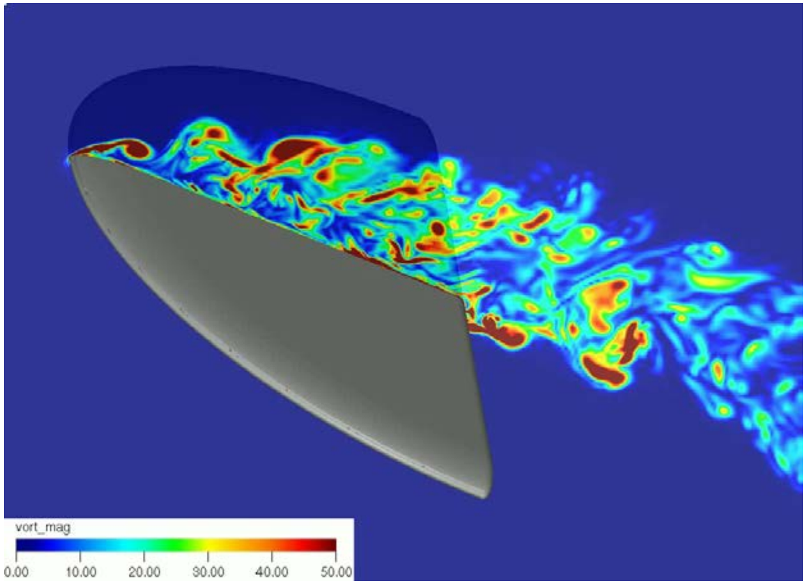
© Exa Corporation Confidential

Active Flow Control

Natural flow



Actuated flow



Exa Corporation

Illinois Institute of Technology, Chicago, IL

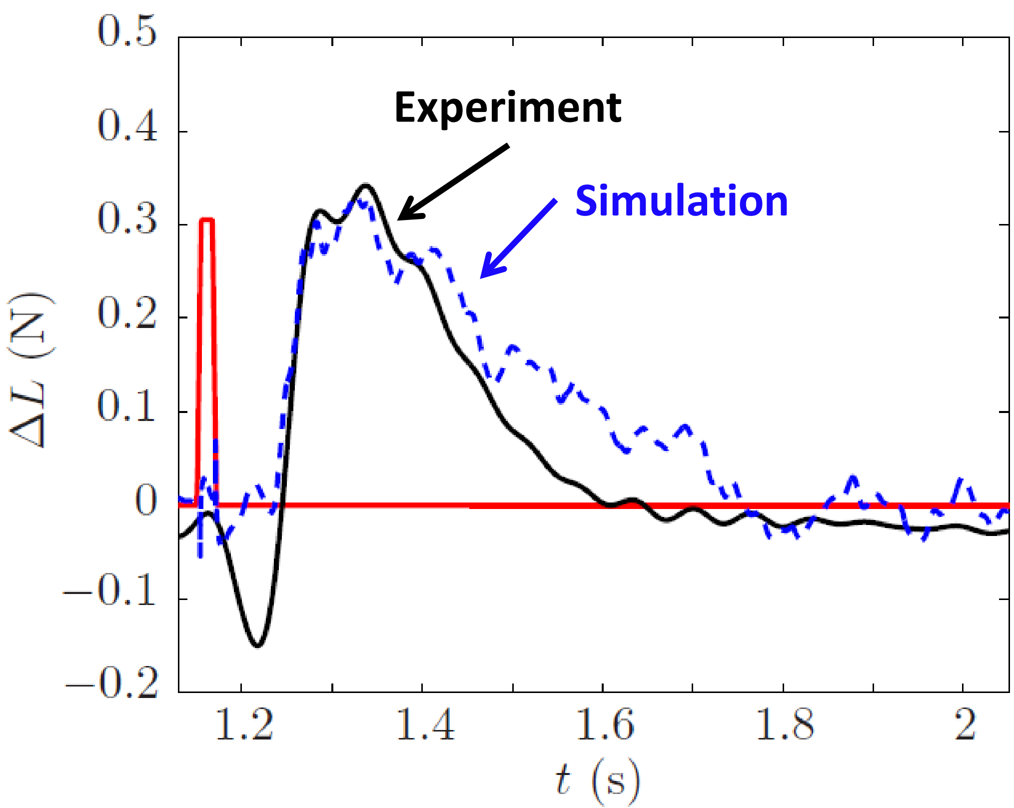
California Institute of Technology, Pasadena, CA

Sources
AIAA 2010-4713
AIAA 2011-3440

© Exa Corporation Confidential

Comparison PowerFLOW - Experiment

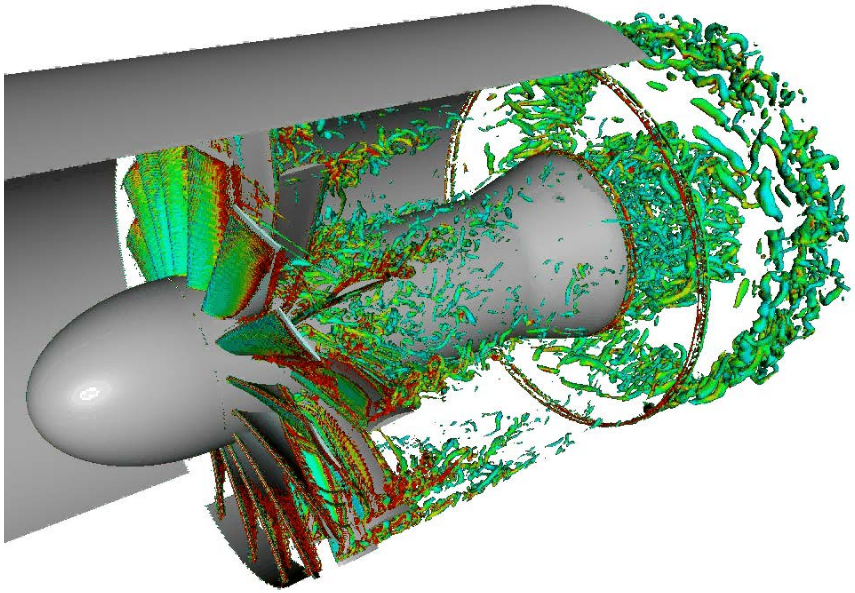
- Transient increase in lift ΔL
  - *Only one cycle of actuation in simulation*
  - *About 60 cycles, phase-averaged in the experiment*

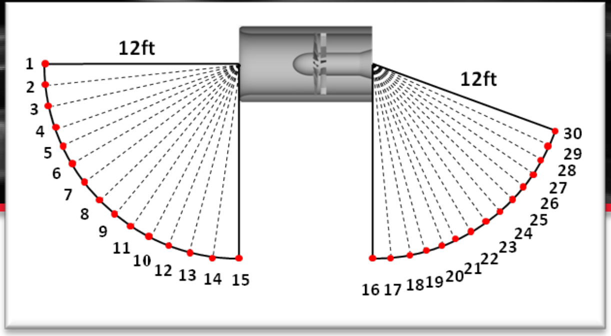


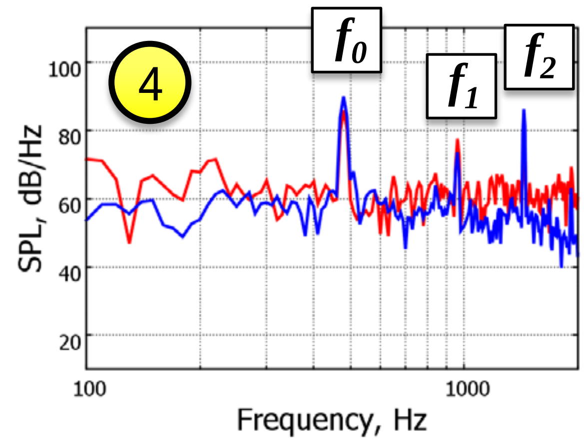
- Good agreement overall
- Peak value and length of the transient lift well captured in simulation

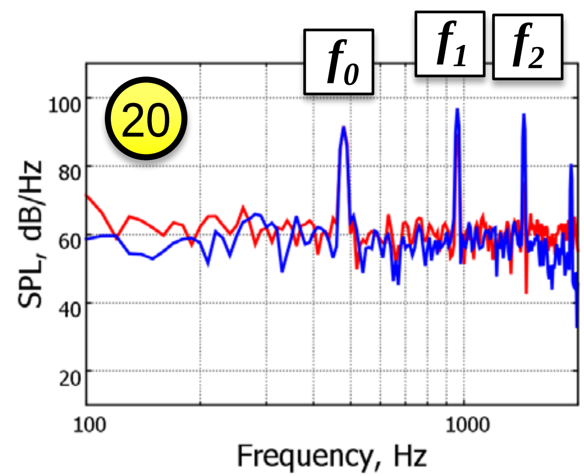
© Exa Corporation Confidential

Fan Noise









Source
AIAA 2012-2287

NASA Experiment
PowerFLOW Simulation

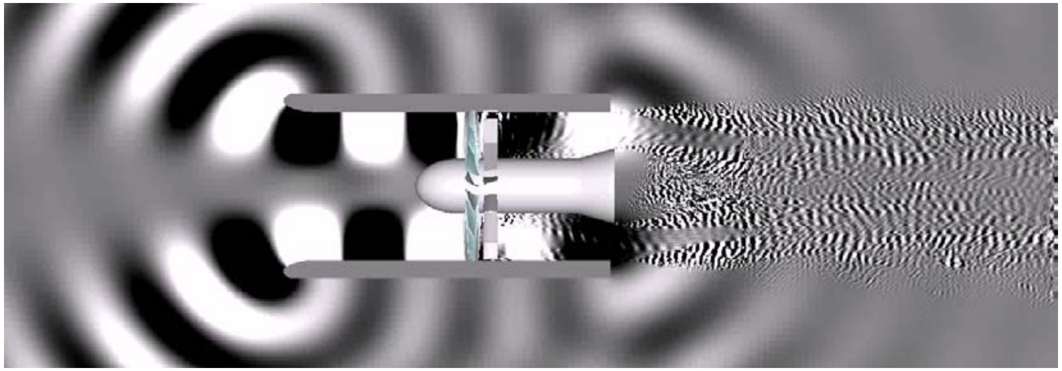
– *Direct results from simulation*
– *Peaks captured at expected frequencies*
– *Broadband content levels in close agreement*

© Exa Corporation Confidential

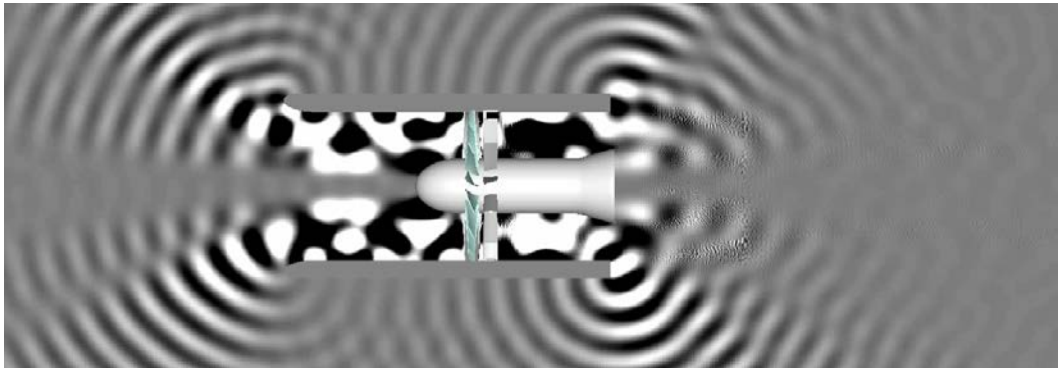
Fan Noise: Band filtered results

- Filtered pressure on narrow bands

Centered on f_1
Filtered [470-490Hz]



Centered on f_3
Filtered [1420-1460Hz]

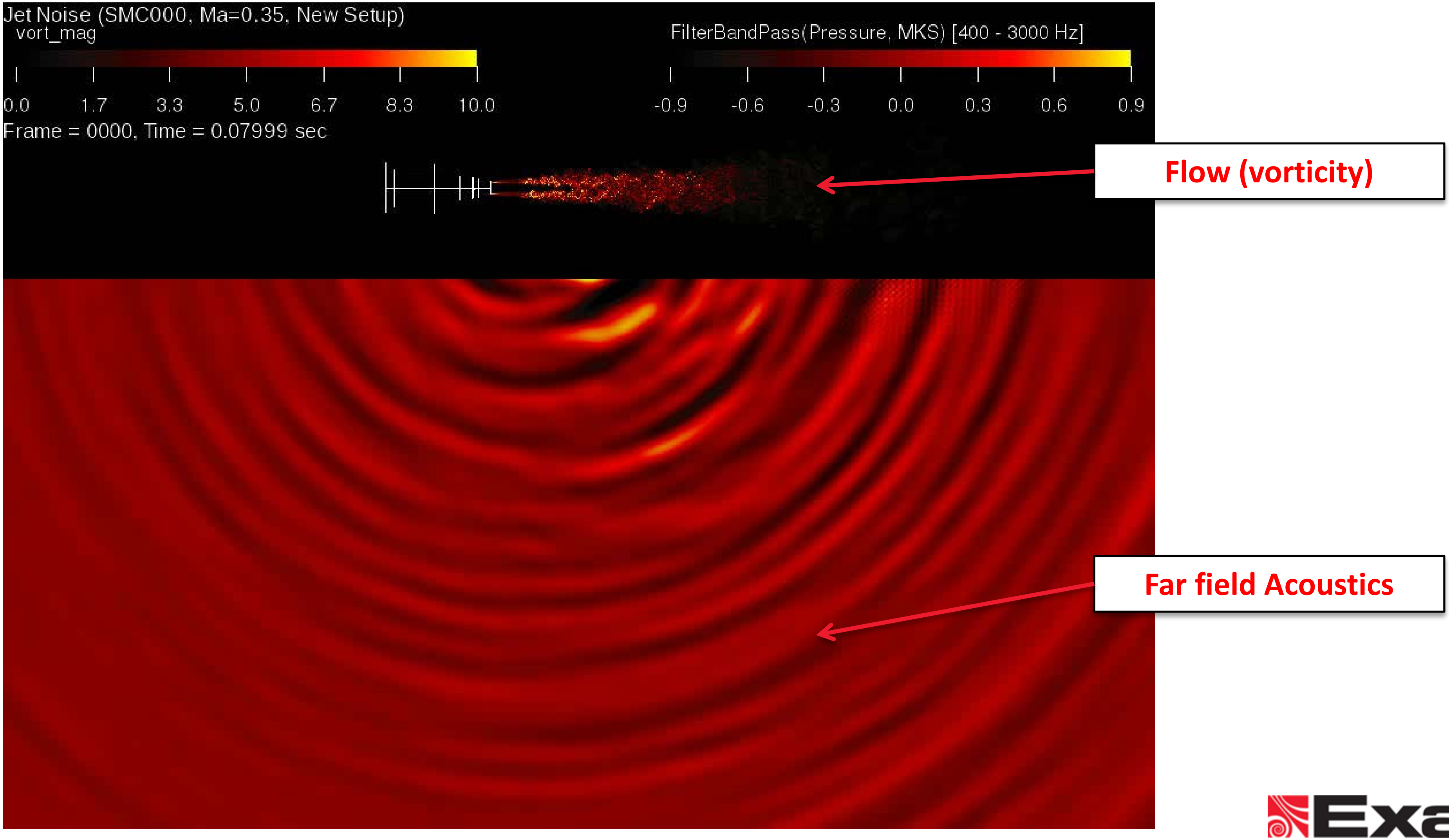


  - *Strong diffraction patterns*
  - *Modal content more complex at 3rd BPF*

© Exa Corporation Confidential

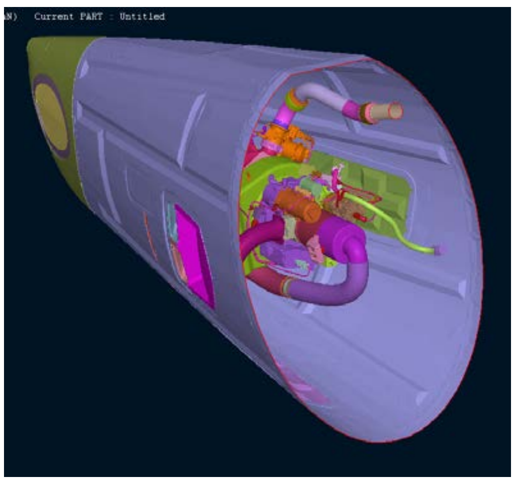
© Exa Corporation Confidential

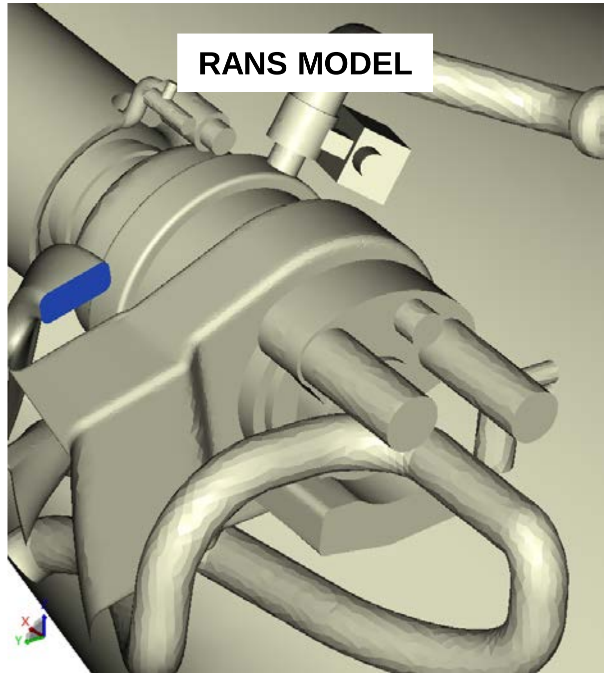
Jet radiated noise

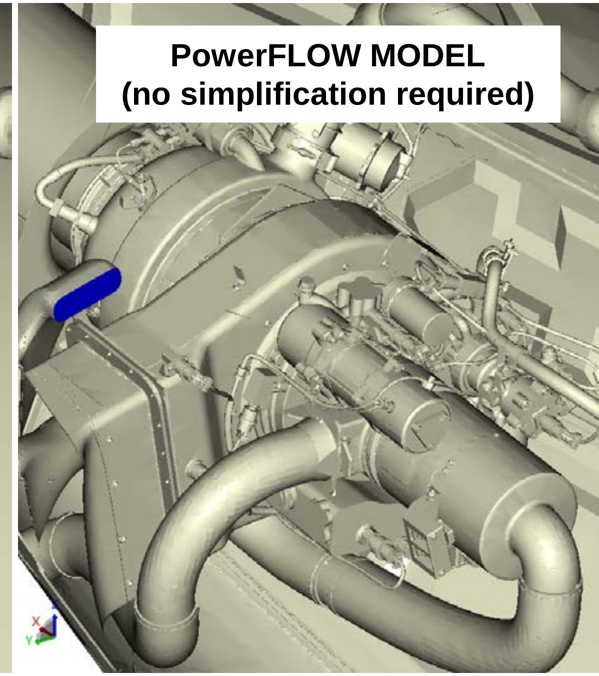


© Exa Corporation Confidential

ECS: Auxiliary Power Unit cooling

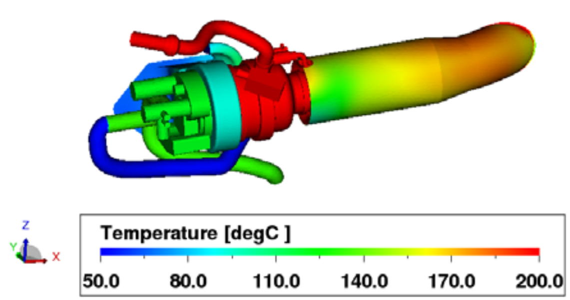


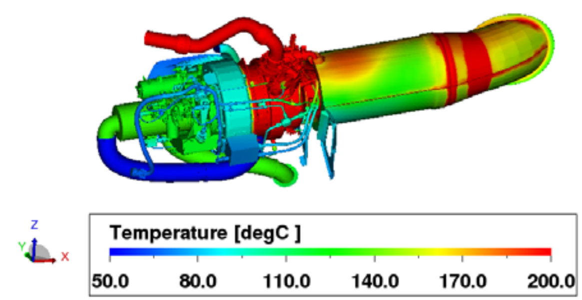




Preparation Time: 25 Days

Preparation Time: 2 Days





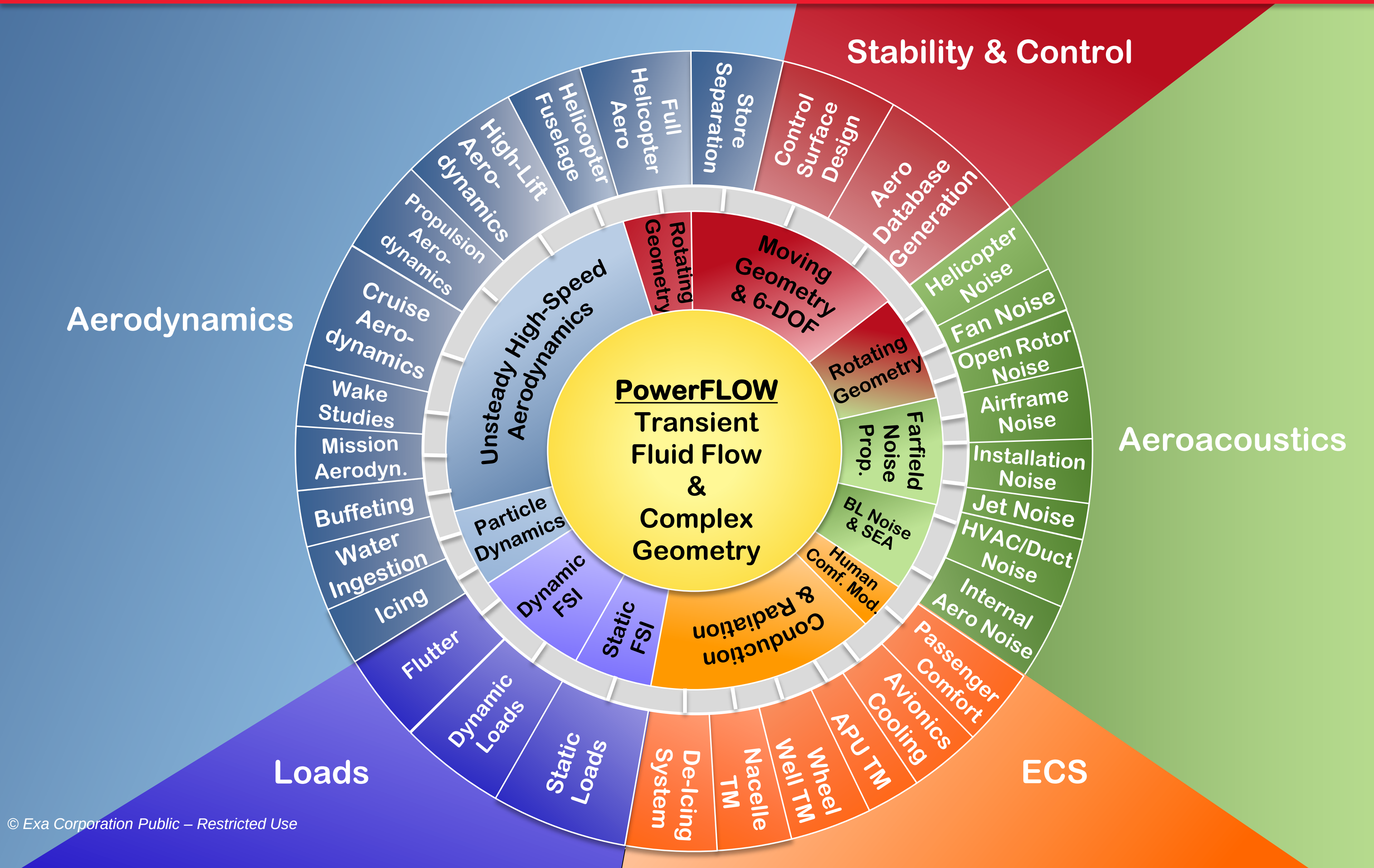
© Exa Corporation Confidential

Overview

- Exa Corporation Overview
- Lattice Boltzmann Method
- Aerospace Applications
- Challenges & Plans

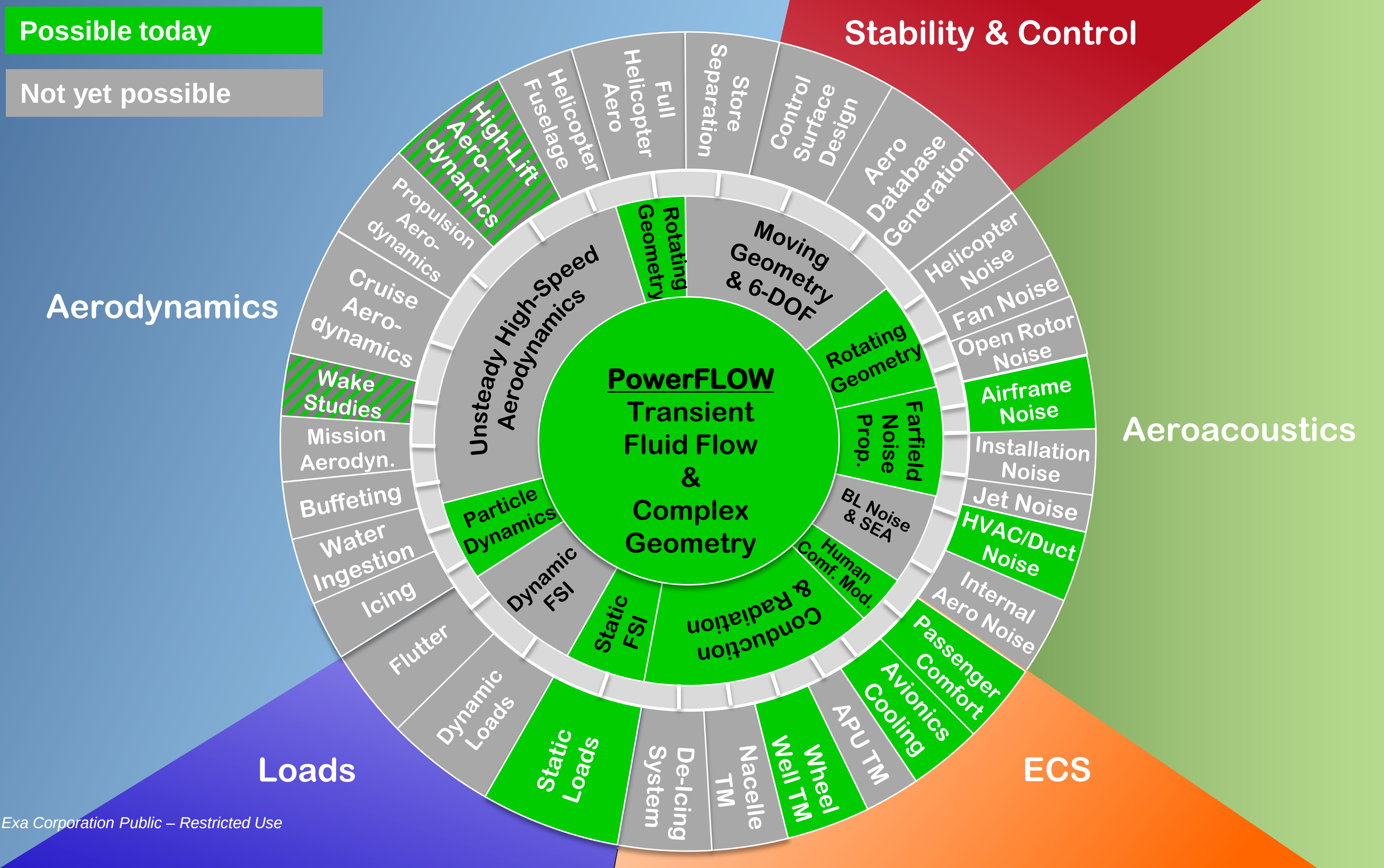
© Exa Corporation Confidential

Aerospace Applications Wheel



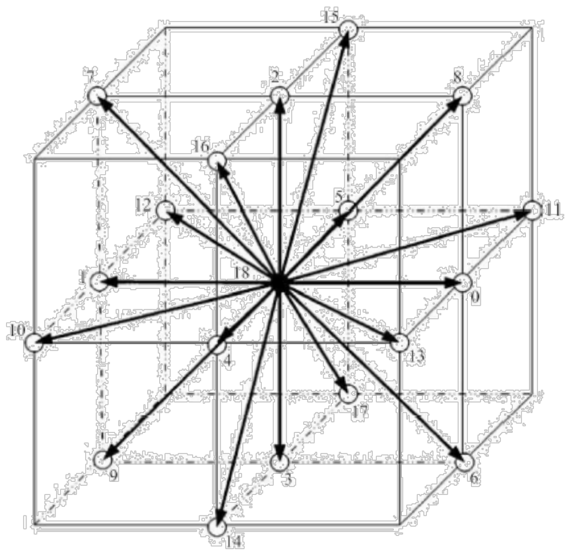
© Exa Corporation Public – Restricted Use

PowerFLOW Capabilities Today

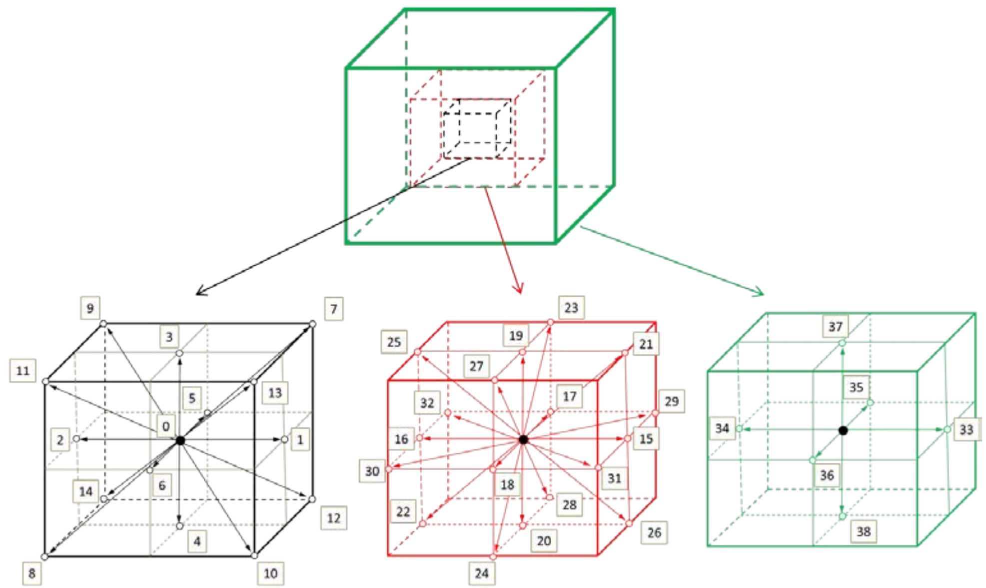


© Exa Corporation Public – Restricted Use

Extension of LBM to Higher Mach Numbers



D3Q19 Model
(freestream Ma_{max}~0.4)



D3Q39 Model
(freestream Ma_{max}~3.0)

Shan,X., Yuan, X.-F., and Chen, H. "Kinetic theory representation of hydrodynamics: a way beyond the Navier-Stokes equation", *J. Fluid Mech.,* vol. 550, pp. 413-441, 2006.

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

Exa

© Exa Corporation Confidential

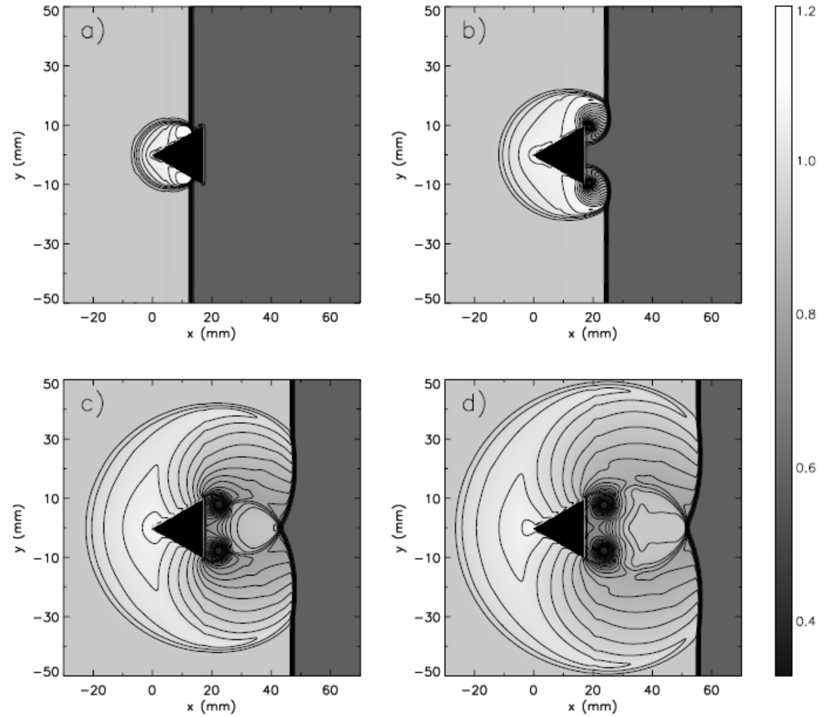
Summary of Current PF Status

- Current technology limited to subsonic flow
  - *Freestream Mach < 0.4 (local max Mach < 0.9)*
- Prototype for High Mach number
  - *Based on "fractional advection"*
  - *Limitations due to slow performance and higher numerical dissipation*
  - *Available today*
- Full High Mach number version
  - *Based on "direct advection"*
  - *Removes all limitations of fractional advection code*
  - *Development ongoing, Beta version planned this year*

© Exa Corporation Confidential

Collision of a Planar Shock with a Finite Wedge

This study is named after the experimental results presented by Schardin [1]



from [3] Fig.1: Density contourplots for the Schardin problem at the following time steps a) $t = 28$, b) $t = 53$, c) $t = 102$ and d) $t = 120\ \mu s$. There were 27 contour levels used, with a minimum of 0.4 and a maximum of 1.1.

[1] H. Schardin: High frequency cinematography in the shock tube , J. Phot Scie , 5:19-26, 1957
[2] S-M. Chang and K-S. Chang: On the shock-vortex interaction in schardin's problem, Shock Waves, 10:333-343, 2000
[3] M. Omang, S. Boerve and J. Trulsen: Numerical Simulation of Shock-Vortex Interactions using regularized smoothed particle Hydrodynamics, Computational Fluid Dynamics Journal, 12(2):32, July 2003

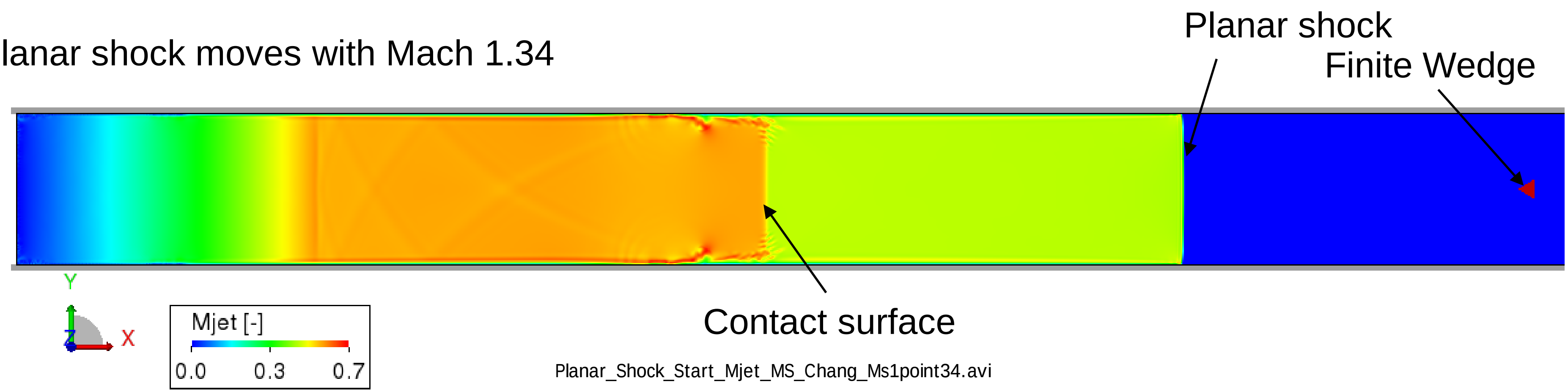
Exa

© Exa Corporation Confidential

Collision of a Planar Shock with a Finite Wedge

Mach_local distribution at a time before the planar shock reaches the finite wedge

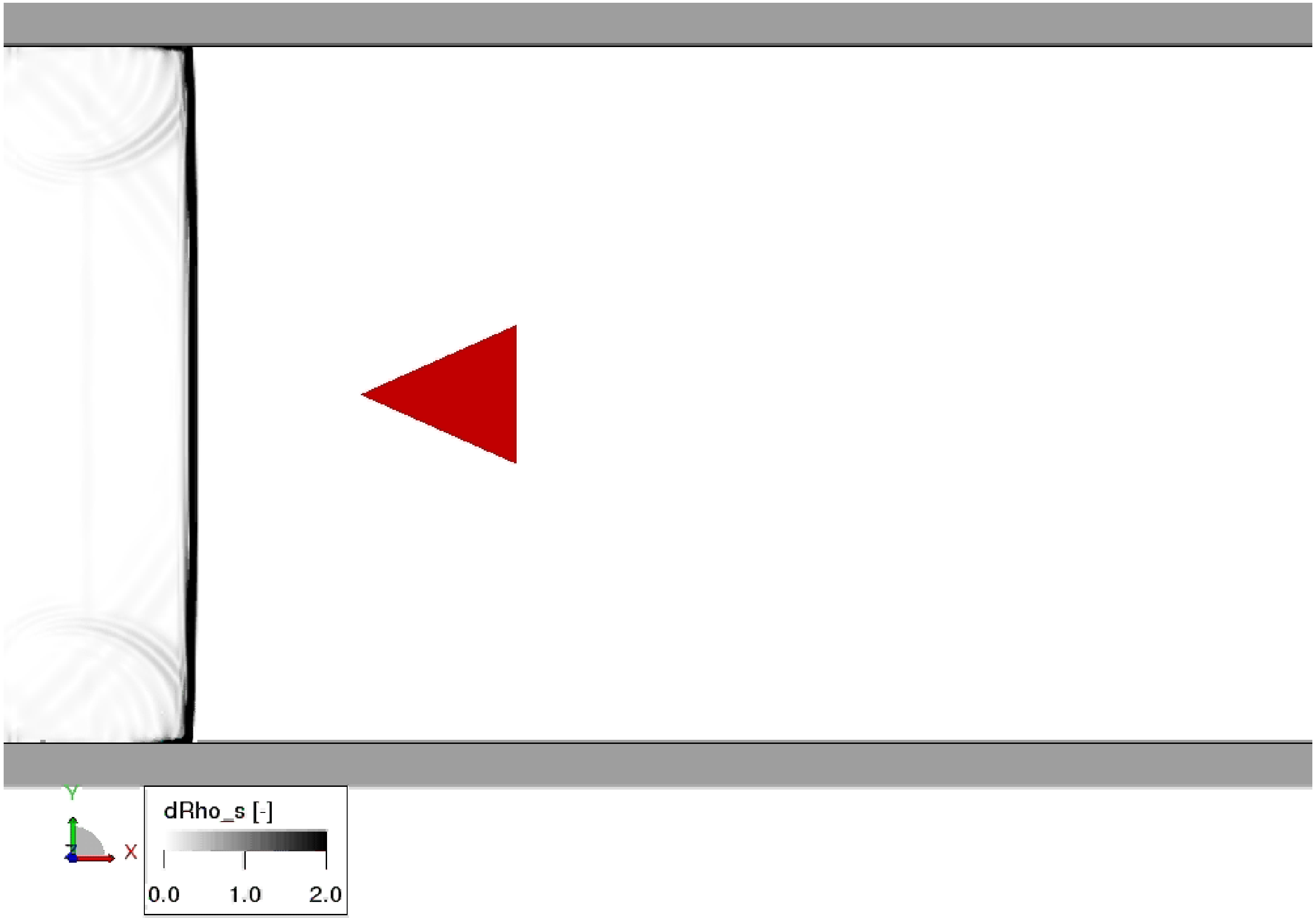
Planar shock moves with Mach 1.34



Animation of the moving planar shock

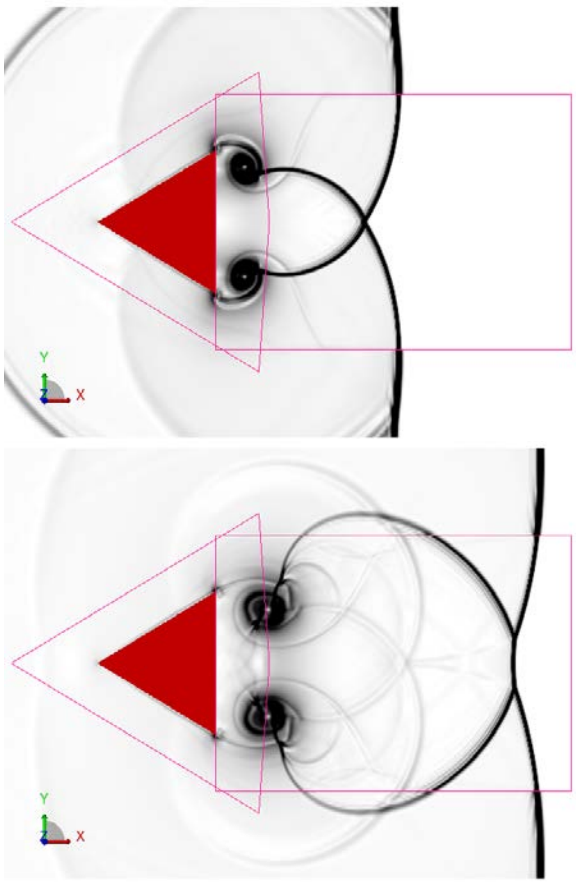
© Exa Corporation Confidential

Collision of a Planar Shock with a Finite Wedge

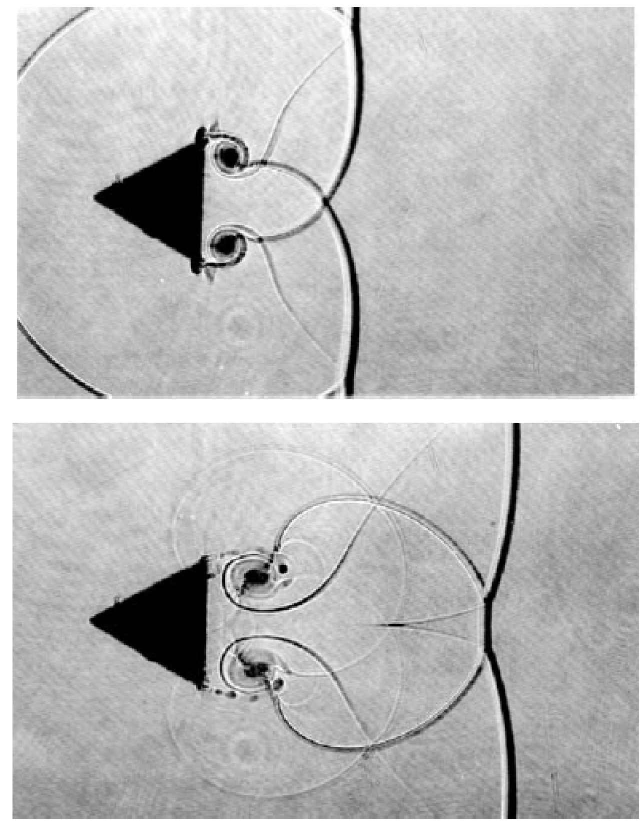


© Exa Corporation Confidential

Collision of a Planar Shock with a Finite Wedge



Simulation

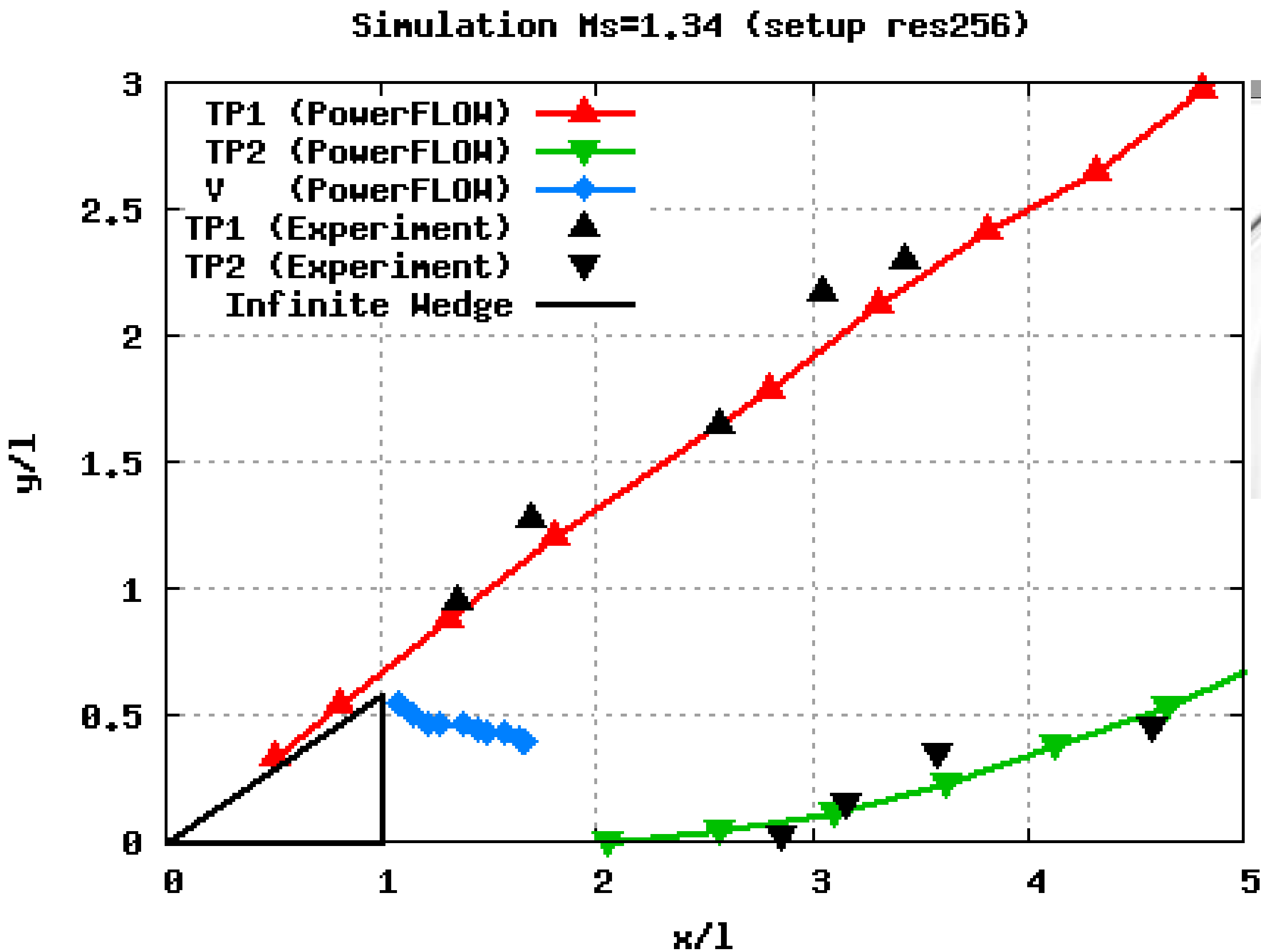


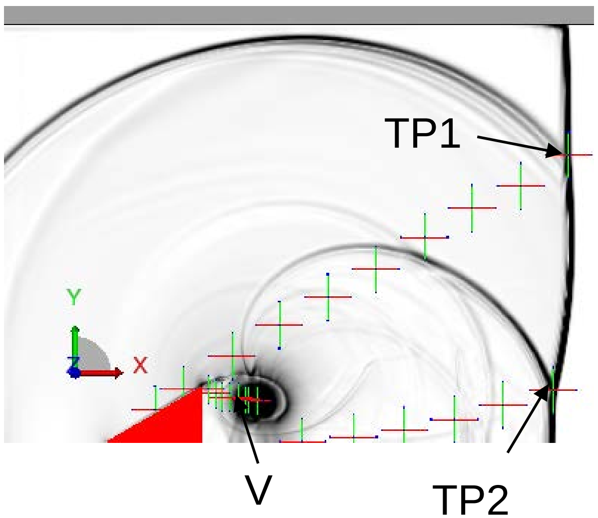
Experiment

© Exa Corporation Confidential

Collision of a Planar Shock with a Finite Wedge

Comparision of triple point trajectory TP1 and TP2 and locus of vortex center V





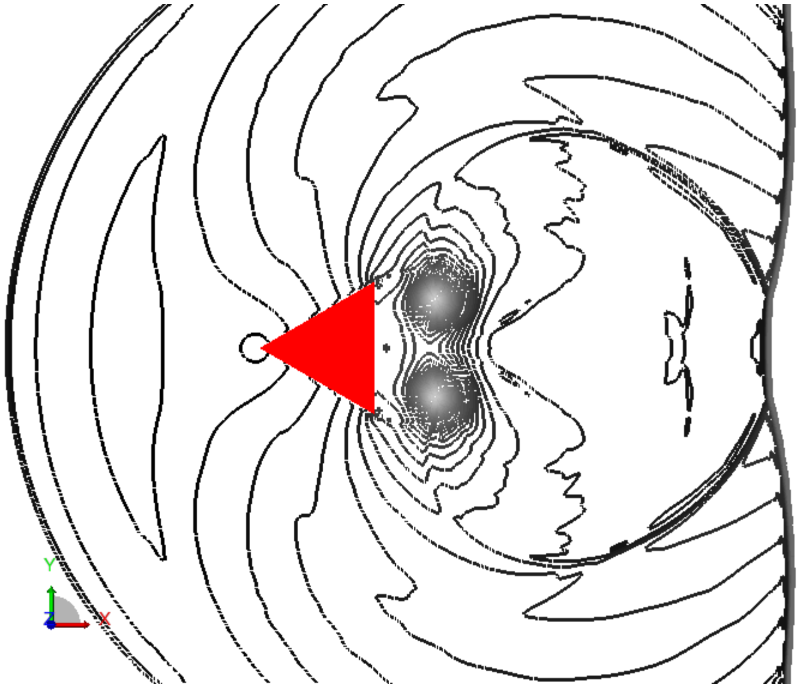
Graphic with PowerVIZ

© Exa Corporation Confidential

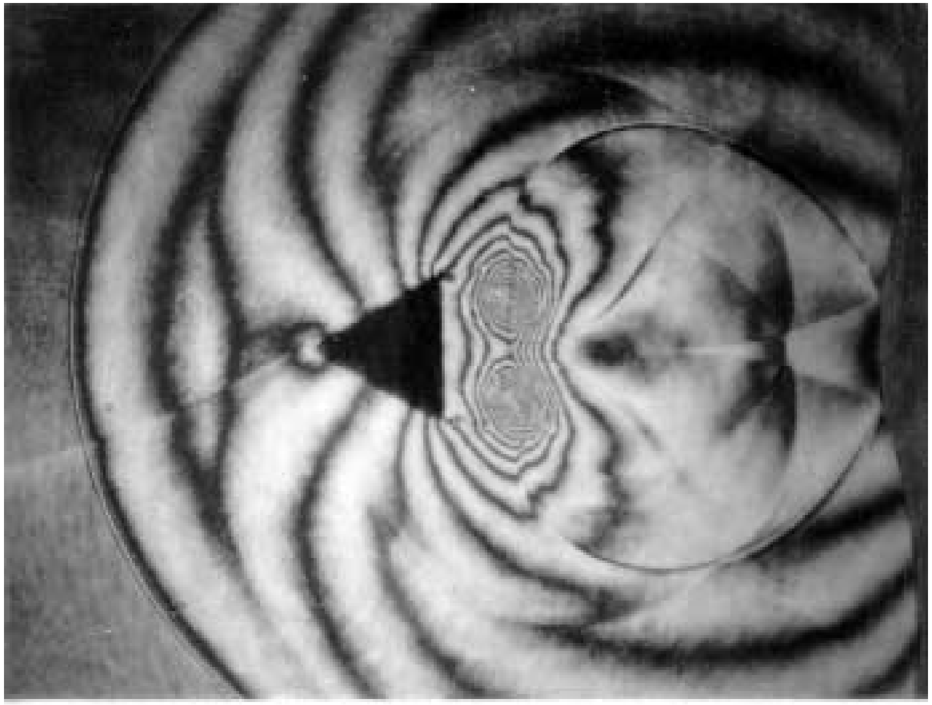
1.3..2012

Collision of a Planar Shock with a Finite Wedge

Density fields



PowerFLOW

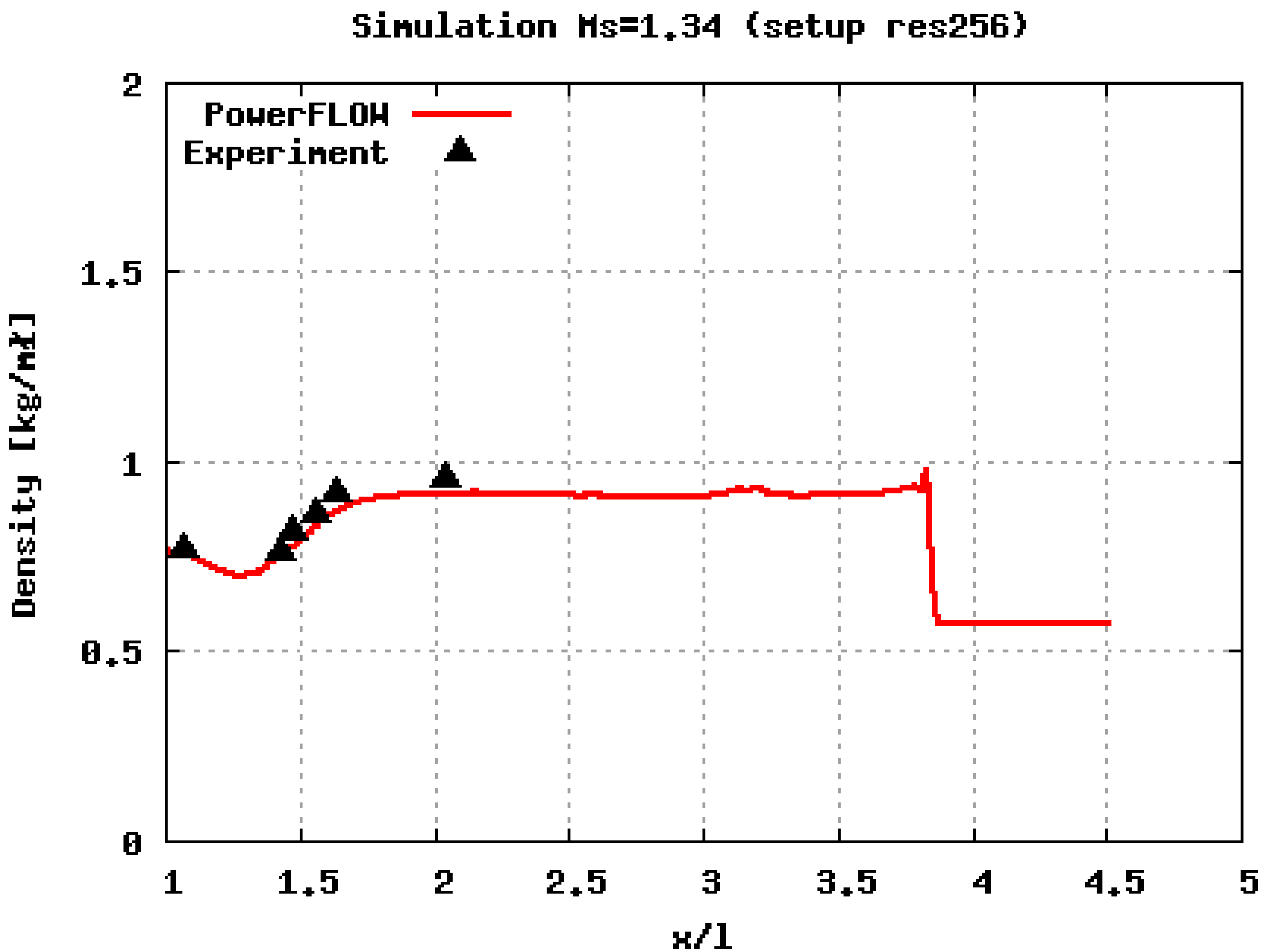


Experiment

© Exa Corporation Confidential

Collision of a Planar Shock with a Finite Wedge

Density distribution along the x-axis behind the wedge

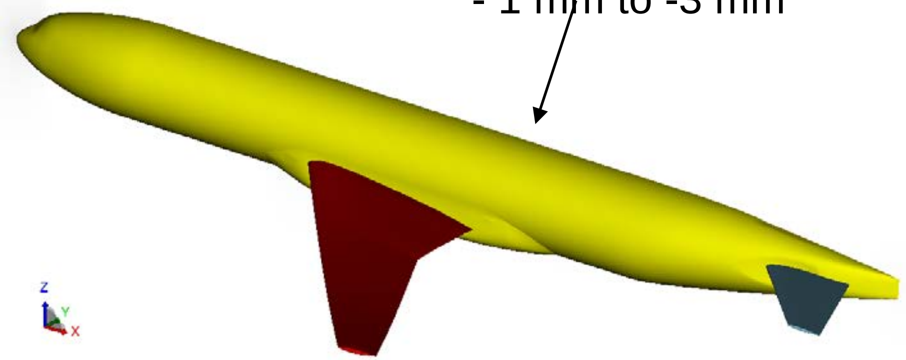


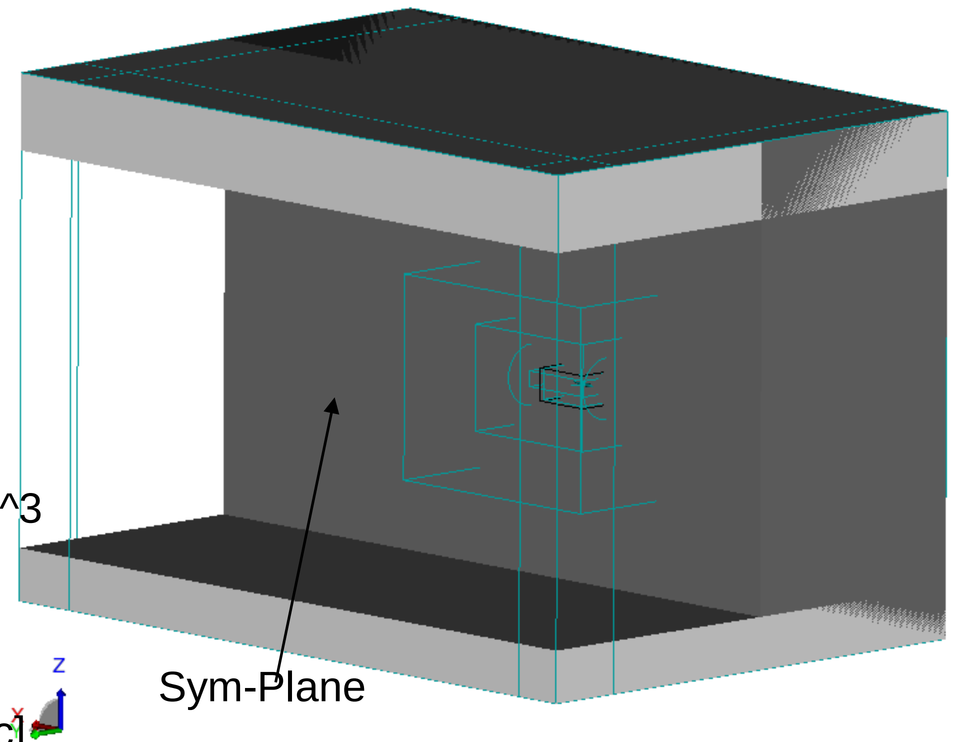
© Exa Corporation Confidential

NASA-CRM (Common-Research-Model)

Setup

Model moved in y-direction
- 1 mm to -3 mm





Simulation Parameters:

L_ref = 0.18914 m
Area_ref = 0.13985 m^2
Ma = 0.85
Re = 5E+06
AOA = 0°, 2°, 3°

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

Sim-Time = (55 to 144) * L_ref/Velocity_Inlet [Sec]

Windtunnel (NTF National Transonic Facility, NASA Langley) :
CL = 0.5 at AOA (Angle of Attack) 3.02° with CD = 0.0275, CM = 0.0378

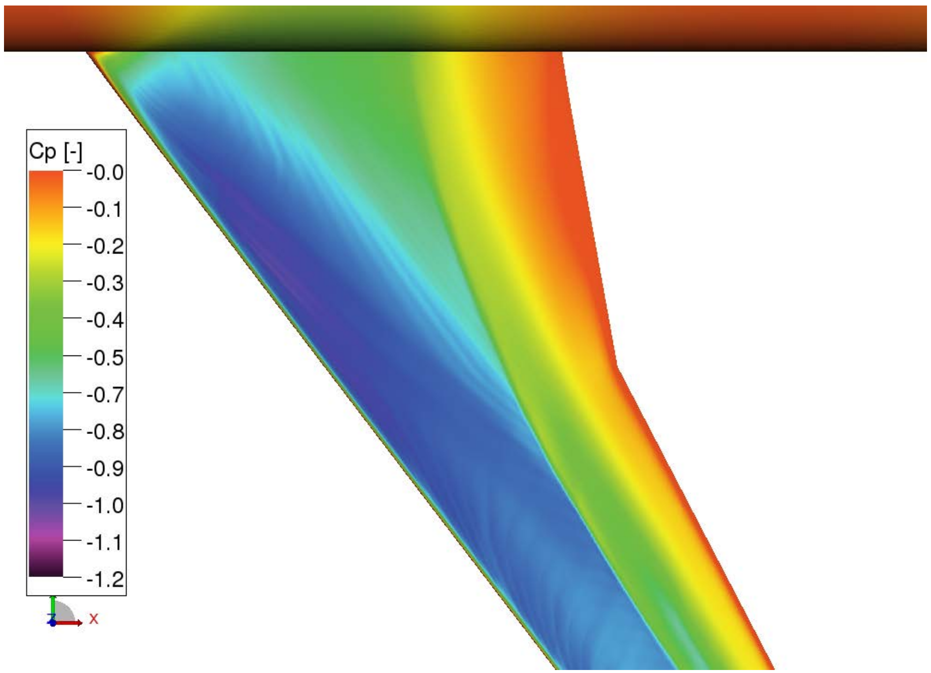
DPW-4 :
CL = 0.5 at AOA (Angle of Attack) 2.34° with CD = 0.027, CM = -0.04025

© Exa Corporation Confidential

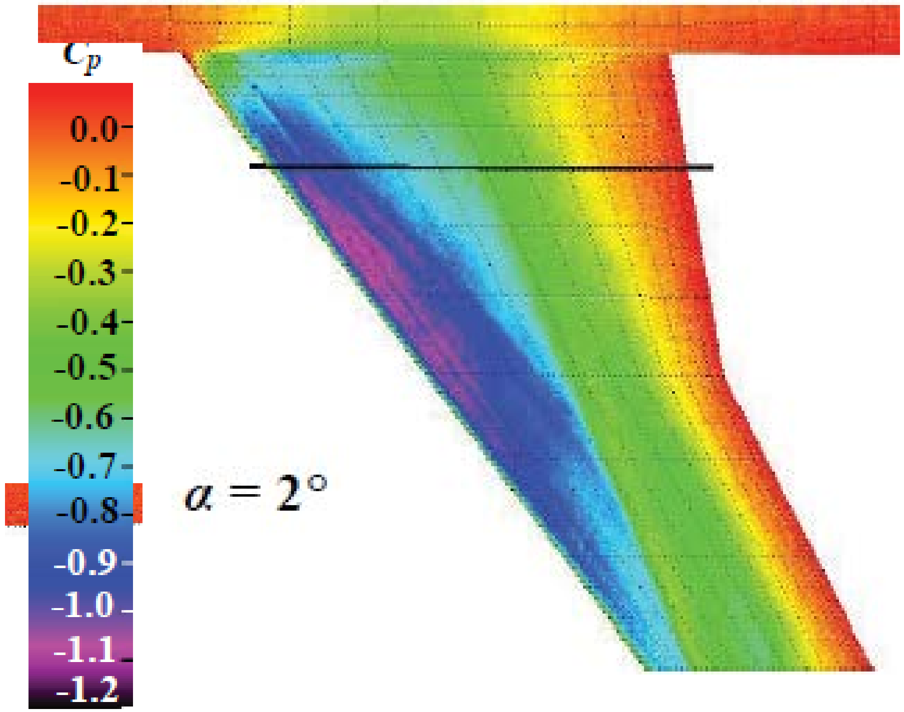
NASA-CRM (Common-Research-Model)
Preliminary Results

Pressure distribution on the wing upper surface
AOA 2°

Simulation

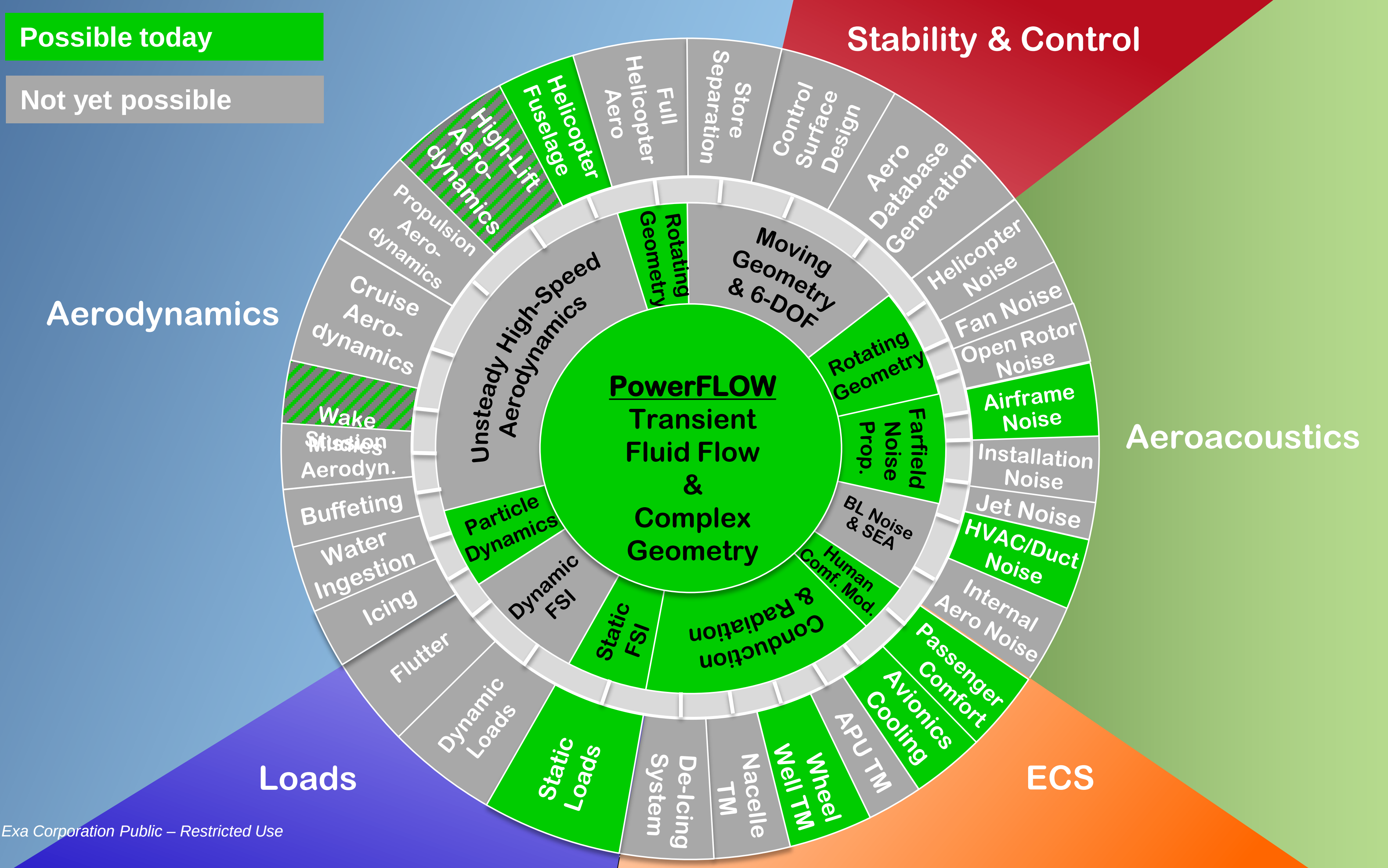


Pressure-sensitive paint measurements



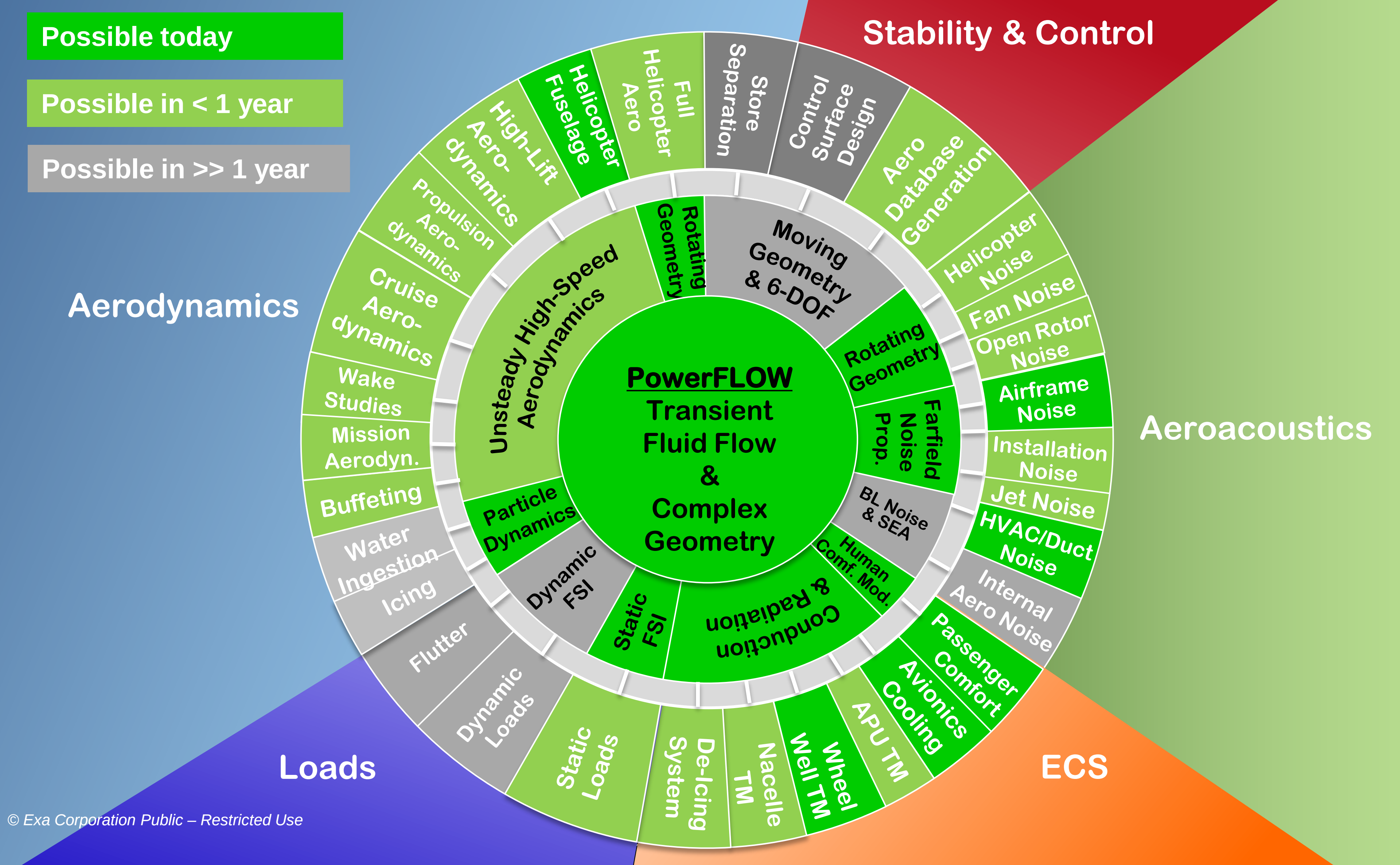
© Exa Corporation Confidential

PowerFLOW Capabilities Today



© Exa Corporation Public – Restricted Use

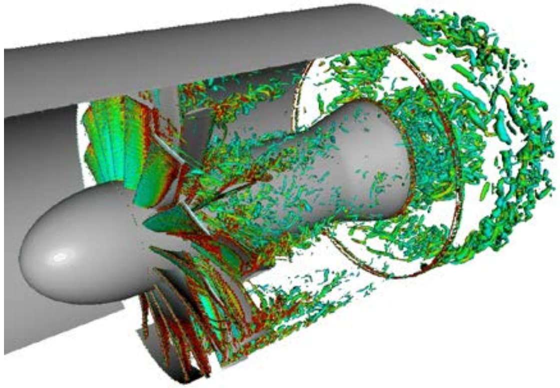
Aerospace Applications Wheel



© Exa Corporation Public – Restricted Use

Enabling Features

- Moving geometry
  - *Rotation available today*
  - *Arbitrary movement: 1-3 years*



- Fluid-Structure Interaction
  - *Static coupling: available today (prototype)*
  - *Dynamic coupling: 2-5 years*

© Exa Corporation Confidential

Simulations of Full Aircraft

G550 - Model scale 20%
Ma=0.2, Re_{MAC}~3M

Aerodynamics case size ~200M cells

Acoustics case size ~2B cells

B747– Full Scale
Ma=0.2, Re_{MAC}~40M

Aero case size ~10B cells

Acoustic case size 50-100B cells

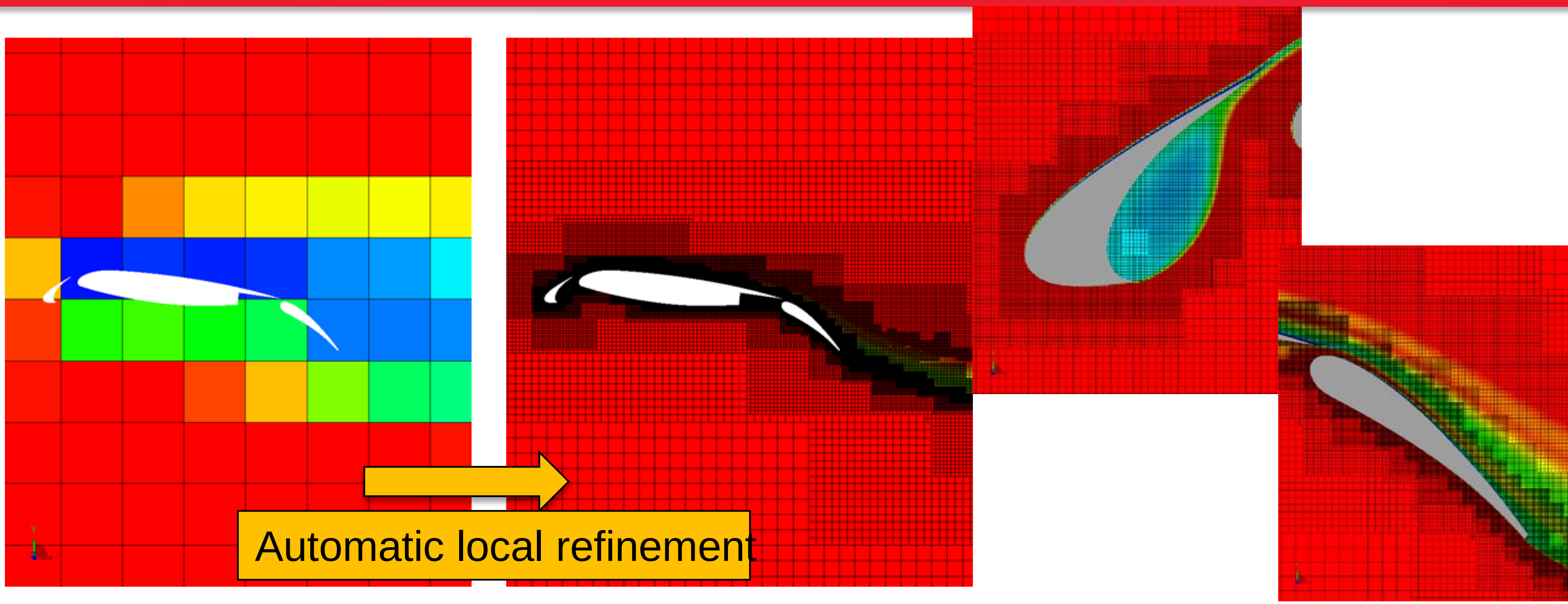
© Exa Corporation Confidential

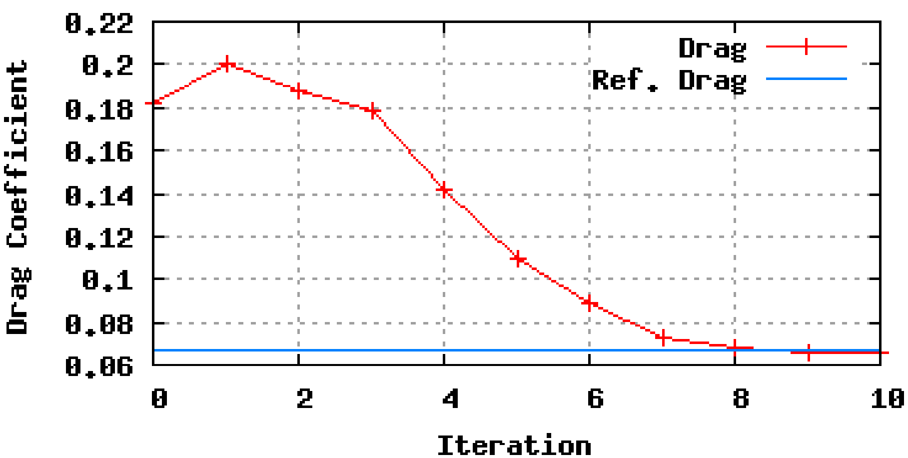
Simulations of Full Aircraft

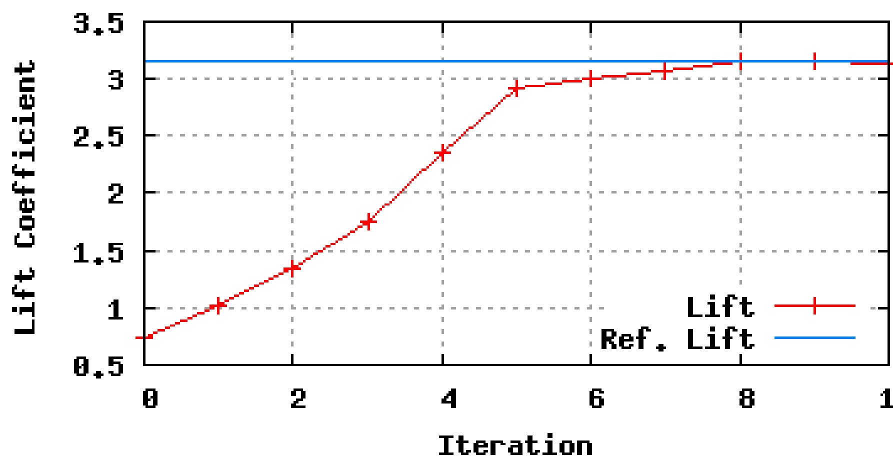
	Today (Business Jet)	Future Requirement (5 years) (Jumbo Jet)
Aerodynamic Case	26 hours on 1000 cores (200M cells)	12 hours on ~ 27,000 cores (10B cells)
Aeroacoustic Case	165 hours on 2000 cores (2B cells)	12 hours on ~170,000 cores (50B cells)

© Exa Corporation Confidential

Adaptive Refinement







© Exa Corporation Confidential

Summary

Accuracy

- LBM offers high accuracy for unsteady & separated flows (including smooth surface separation)
  - *Now including supersonic flows*
- Open question: Is the use of a wall model limiting?

Speed

- LBM is a very efficient unsteady solver
- Full plane (aerodynamics) will be possible long before 2041

Robustness

- Key advantage of LBM

© Exa Corporation Confidential