Engineering, Operations & Technology
Boeing Research & Technology

Overset CFD Technology Development and Application at the Boeing Company

Jeffrey Slotnick
Boeing Research & Technology, Huntington Beach, CA, USA

11th Symposium on Overset Composite Grids and Solution Technology
Dayton, OH, USA
October 15–18, 2012

Acknowledgments

- **Boeing Commercial Airplanes**
  Jonathon Elliott, Emanuel Setiawan

- **Boeing Defense, Space & Security**
  Robert Narducci, Ted Meadowcroft, Leonel Serrano

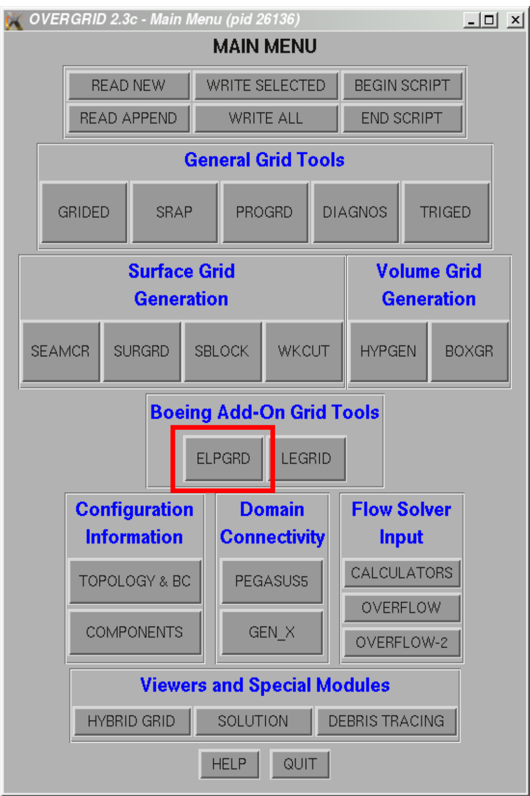
- **Boeing Research & Technology**
  Mark DeHaan, Tony Sclafani, C.F. Shieh, Arvin Shmilovich, Eric Unger, C-J Woan, Yoram Yadlin

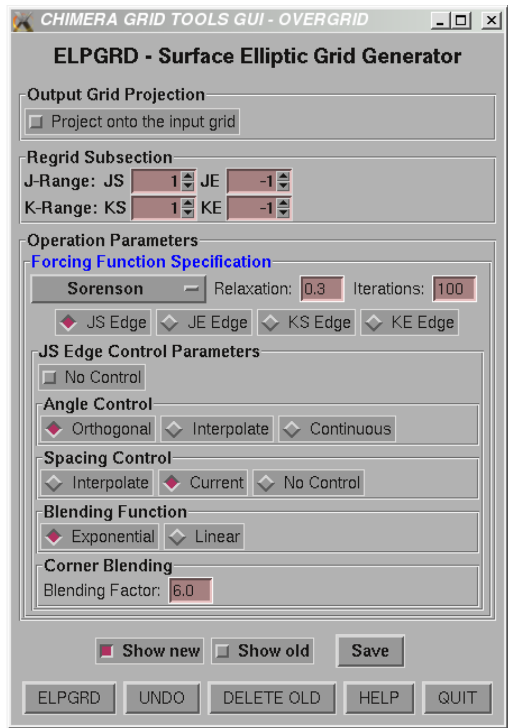
Outline

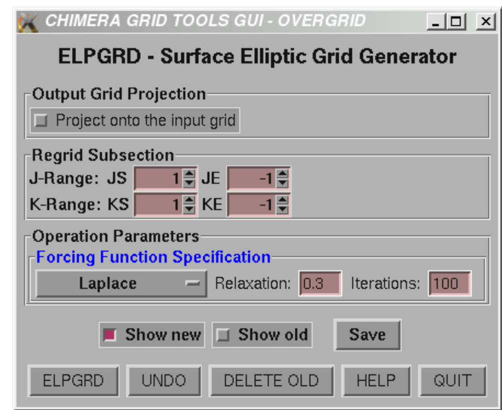
- **Tool and Process Enhancements**
  - OVERGRID
  - Scripting Utilities
  - Automation Systems
- **Preliminary Evaluation of OVERFLOW Adaptive Mesh Refinement (AMR) Technology**
- **Brief Survey of Overset Applications**
  - Rotorcraft
  - Active Flow Control (AFC)
- **Concluding Remarks**

Enhancements to Overset Tools and Processes

- **Addition of elliptic smoothing capability to OVERGRID (ELPGRD)**
  - Routines extracted from Boeing-developed grid generation code
  - Surface smoothing only (at the moment)
  - Four options: Laplace, Sorenson, Thomas-Middlecoff, Smooth Initial
  - Can project to the surface

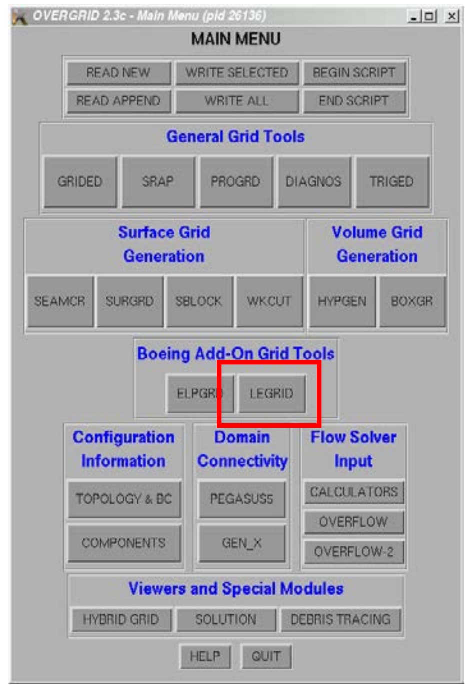


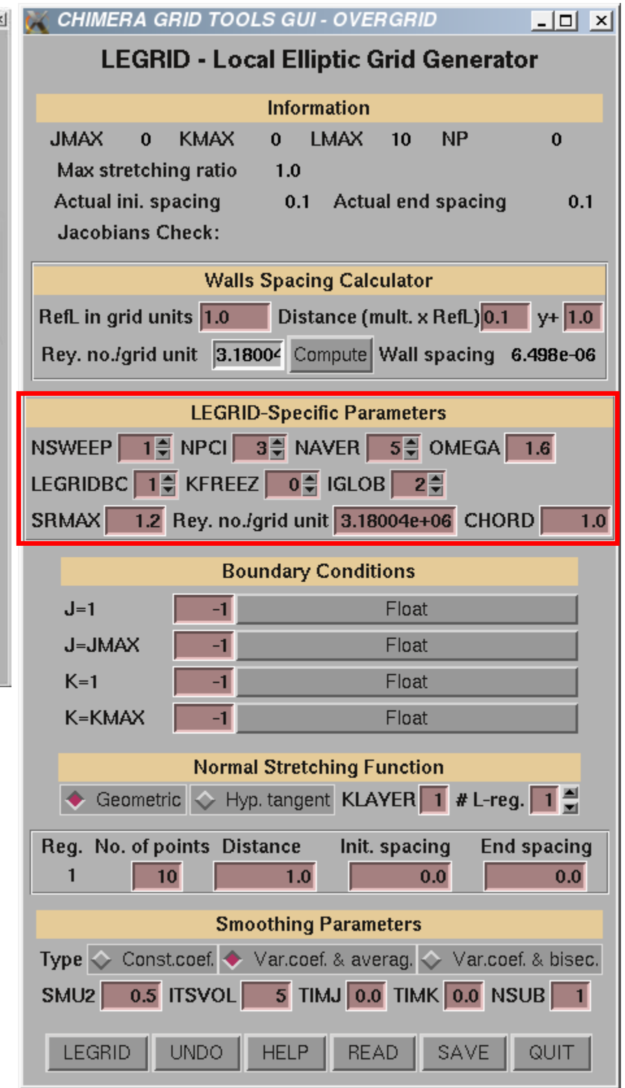




Enhancements to Overset Tools and Processes

- **Addition of LEGRID capability to OVERGRID**
  - Hyperbolic grid generator with elliptic smoothing during marching procedure
  - LEGRID v2.5b July 2012
  - Layout based directly on HYPGEN GUI with one additional input block for LEGRID-specific parameters
  - Allows users the ability to quickly generate grids in a manual fashion

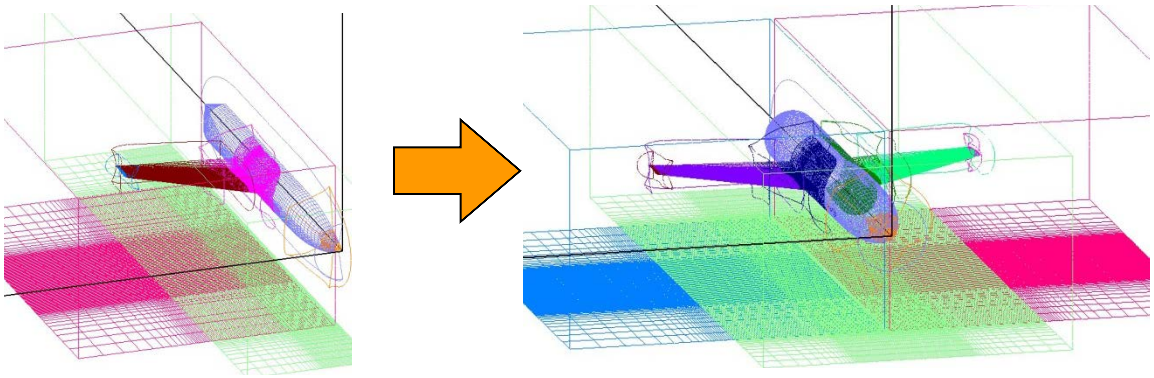




Enhancements to Overset Tools and Processes

OVER_reflect

- Python script to automatically create a full-configuration grid system from a symmetric half-body grid system
- Requires pre-existing Chimera Grid Tools (CGT) configuration script that defines the half-body grid system
  - Creates reflected, periodic, or full grids for the new configuration along with the appropriate (and properly indexed) *.ovfi files
  - Provides appropriate modifications to config.tcl and inputs.tcl
  - Creates/modifies box definitions within the inputs.tcl file as needed.
  - Creates all new reflected and/or full-type HCUT information in the inputs.tcl file (The member, include, and exclude lists will be modified as appropriate.)
  - Creates all new reflected and/or full-type manual holecutting information in the inputs.tcl file.



Enhancements to Overset Tools and Processes

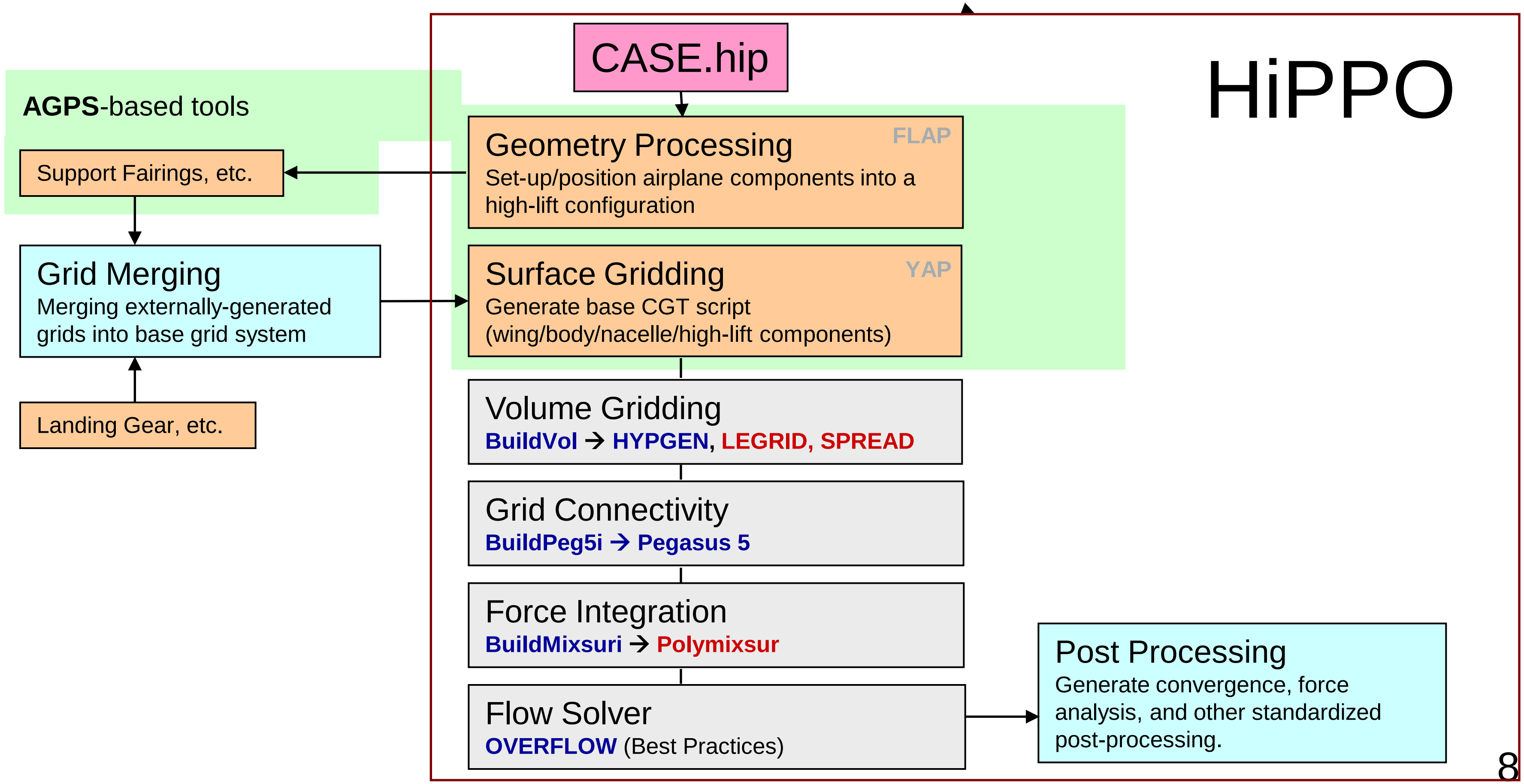
makeCGT

- Python script to automatically create a base CGT script system from a pre-existing grid system built manually → IN DEVELOPMENT
- Requires an OVERFLOW grid.in, over.namelist, PEG5 input file, and (optionally) a mixsur input deck.
  - The multi-block overflow grid is broken into single-block volume and surface grids which are placed into a */model* directory. The grid names are set by the OVERFLOW input deck (and must correspond to the names in the PEG5 input deck). Both double and single precision grid files are accepted.
  - An *inputs.tcl* file is created based on presumed defaults and information provided by the OVERFLOW and PEG5 input decks. Manual hole cutting directives in the PEG5 input deck are supported including the use of phantom surfaces (providing the phantom surfaces are supplied).
  - A *config.tcl* file is created
  - OVERFLOW input files for each grid (.ovfi) are created using the solver input deck with family names added based on (optionally) the mixsur input deck. Note that this can cause some solid wall to be split into multiple parts.
- Future enhancements:
  - Improved family name functionality
  - Volume mesh generation directly through the *inputs.tcl* file

Enhancements to Overset Tools and Processes

Hift-Lift Pre-Processing for OVERFLOW (HiPPO)

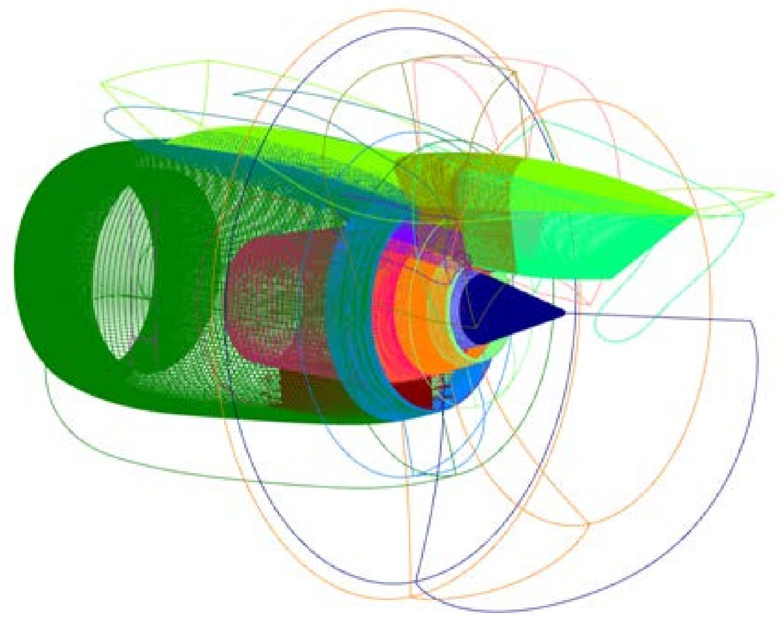
- Process automation system (based on CGT grid scripting) used to generate production level OVERFLOW solutions from geometry through post-processing



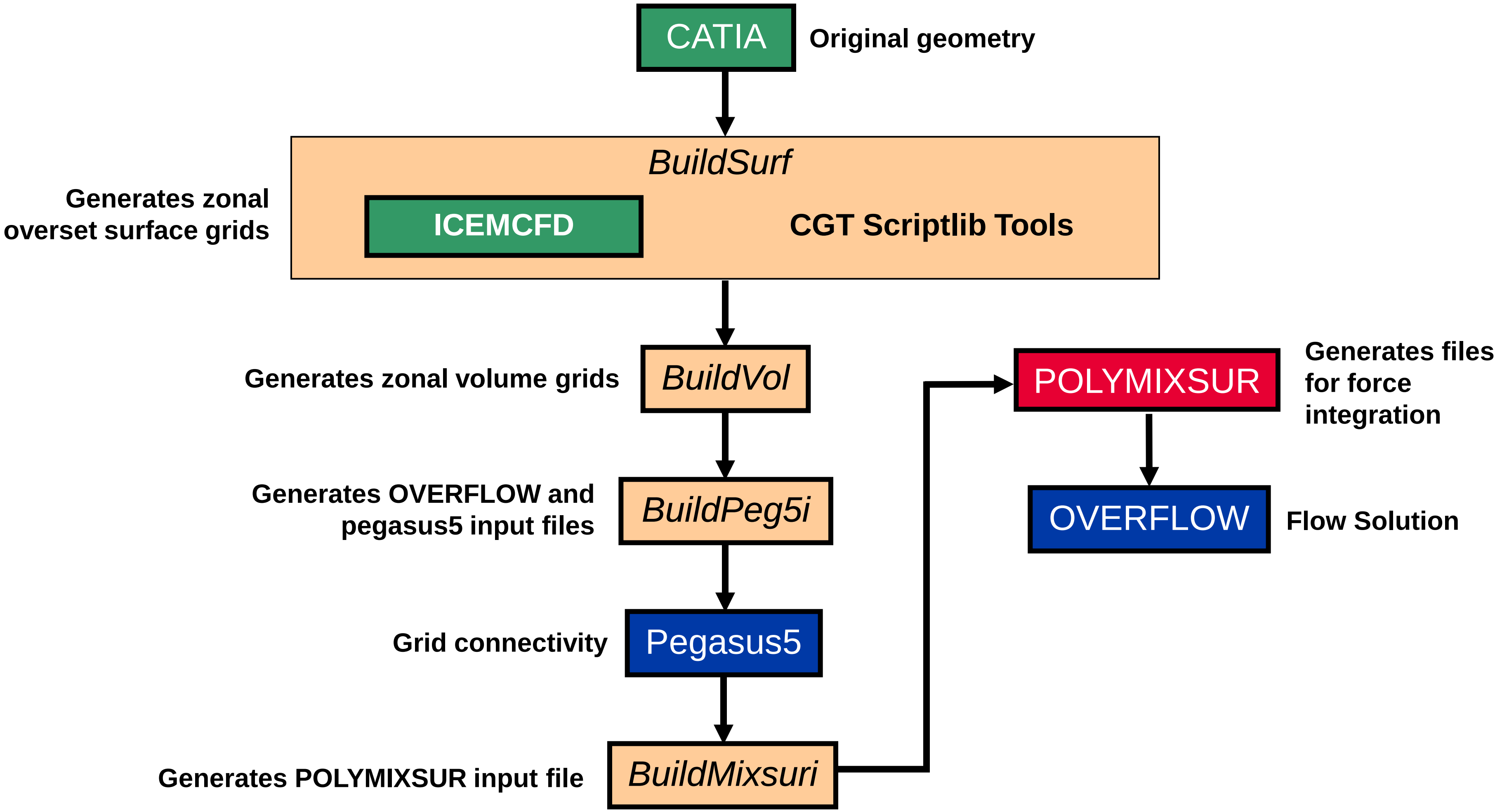
Enhancements to Overset Tools and Processes

AutoNac

- Process automation system used to rapidly generate OVERFLOW-ready grid systems for modern transport airplane engine geometries, including pylon connectivity to main wing
  - Designed for both powered and flow-thru nacelles
  - Has been used on a wide array of production and advanced design engines
- Takes advantage of technology available in ICEMCFD



AutoNac Process

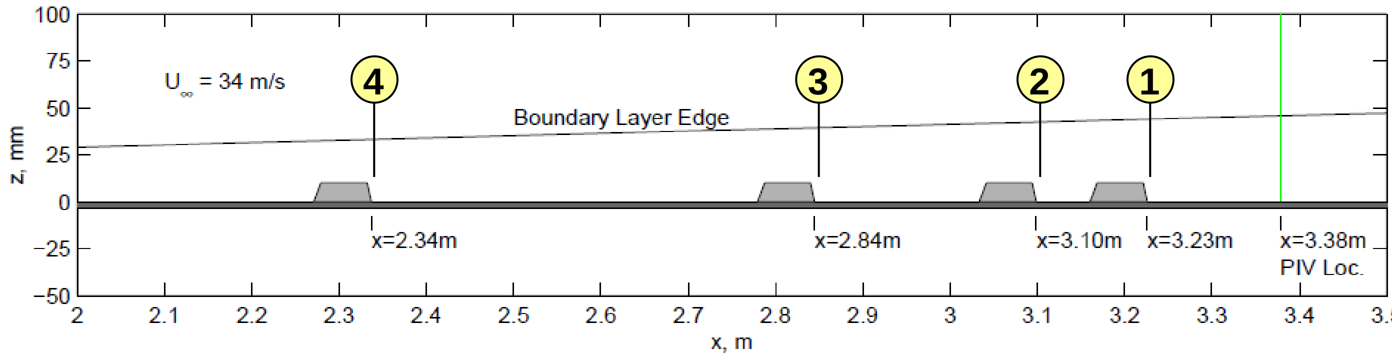


OVERFLOW AMR

- **Efforts are underway to productionize (establish best practices and automate wherever possible) adaptive mesh refinement (AMR) technology in OVERFLOW**
  - Near-Body: Vortex Generator (VG) on a Flat Plate
  - Off-Body: 777-200 High Lift Configuration

Vortex Generator (VG) on a Flat Plate
AIAA Paper 2002-3160*

*Allan, B. G, Yao, C. S., Lin, J. C., “Numerical Simulations of Vortex Generator Vanes and Jets on a Flat Plate,” June 2002.



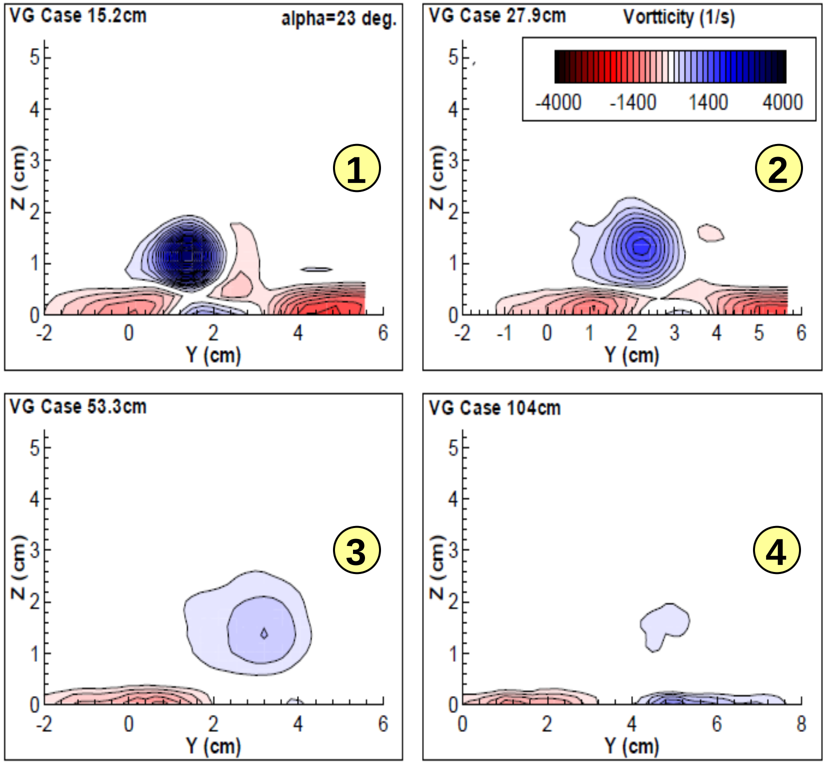
<u>NASA Langley 20x28-inch Shear Flow Tunnel</u>

Geometry and Flow Condition

- VG length = 2.8”
- VG height =0.4”
- VG alpha = 23º
- Freestream Mach = 0.098
- Fully turbulent boundary layer

Velocity Data

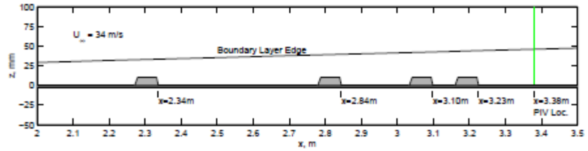
- Particle Image Velocimetry (PIV) system
- Four stations: Δx = 6”, 17”, 27.3”, 46.9”

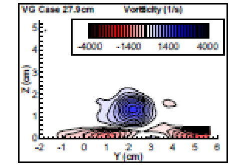


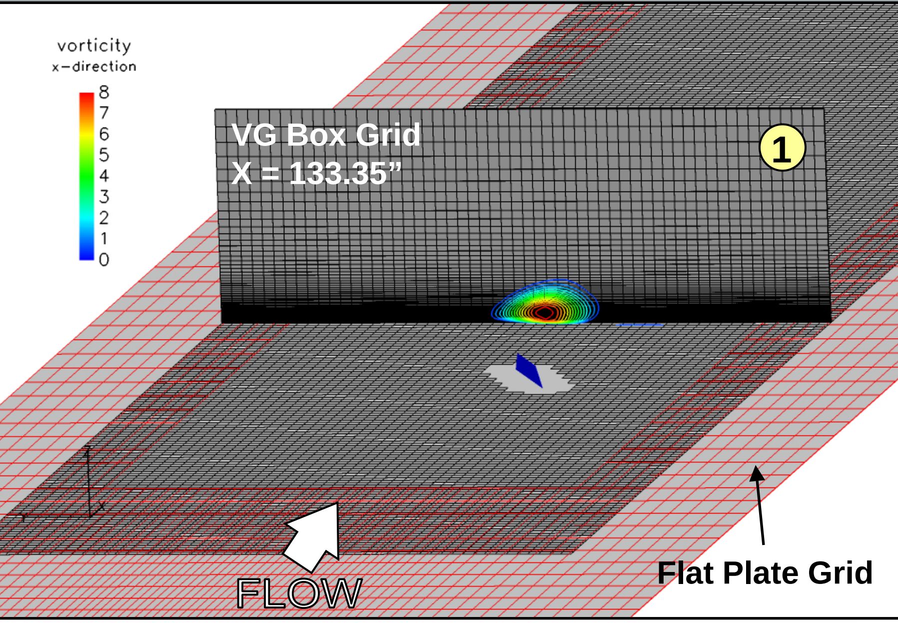
Vortex core position normalized by boundary layer height at station 1 (δ_1 = 1.77”) and tracked as an increment from VG’s base TE

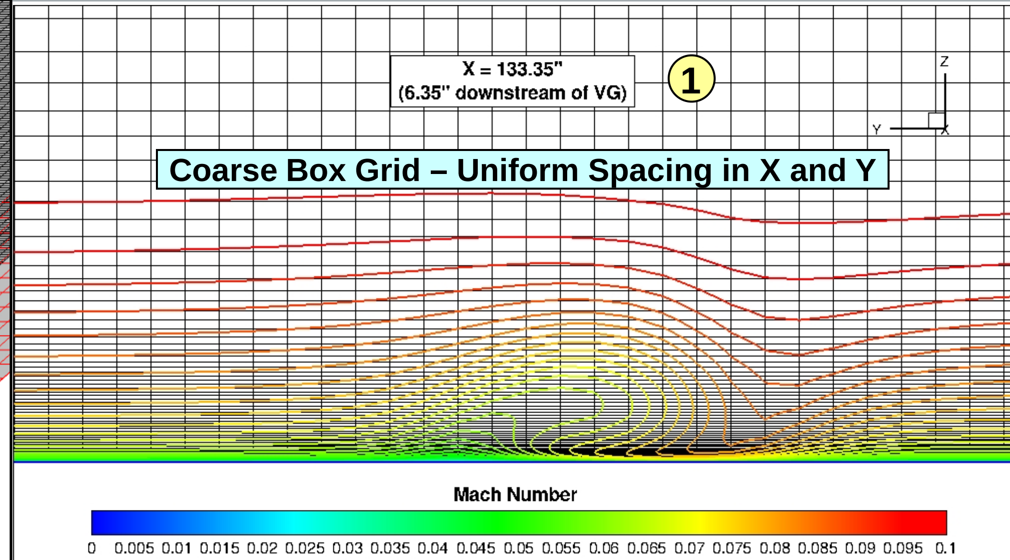
VG on a Flat Plate

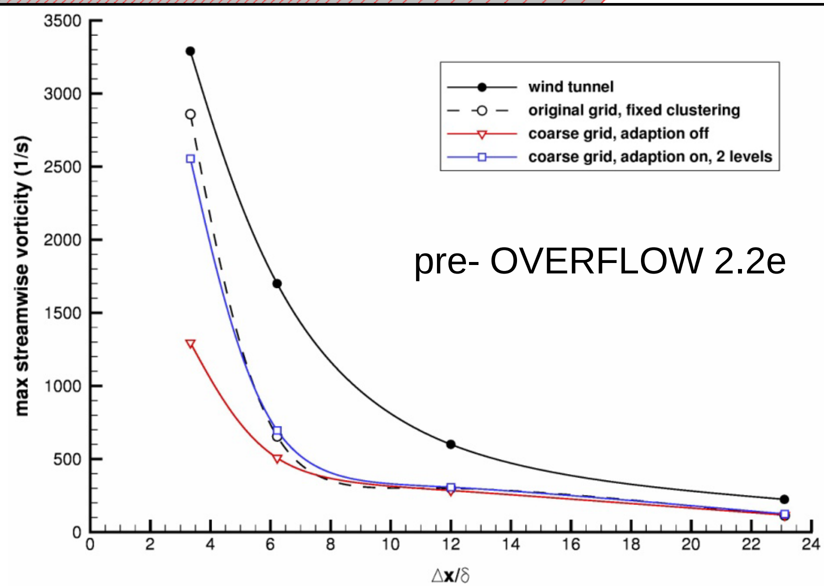
Preliminary OVERFLOW Results

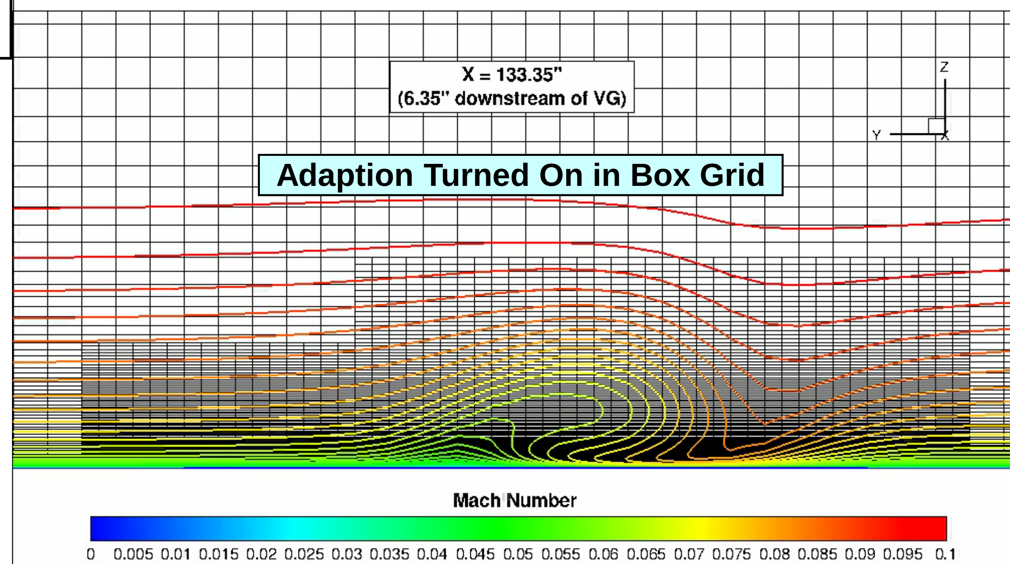






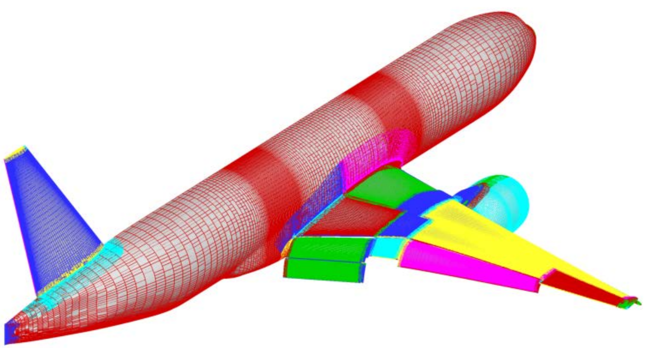


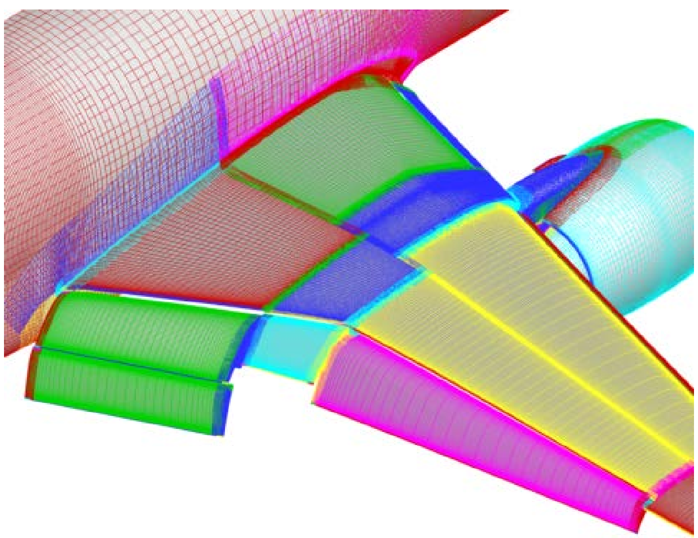


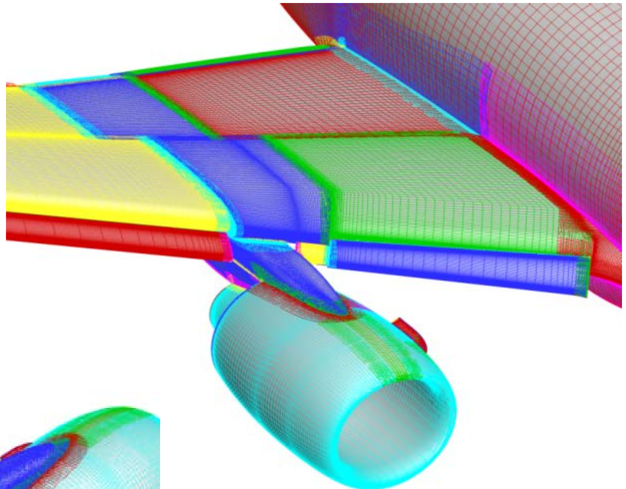


Overset Grid Adaptation
Evaluation of Off-Body Grid Adaptation for High-Lift

- 777-200 landing configuration
  - Overset grid system generated using HiPPO automation package
  - Wing/body/nacelle/pylon/vertical tail half-body configuration
  - 152 zones, 47.2M points
  - F30, flap and slats gapped (no spanwise seals)
  - Flow thru engine (with chine)







Overset Grid Adaptation

Evaluation of Off-Body Grid Adaptation for High-Lift

- **Simulation Details:**
  - Used original component grids, but manually built overset domain connectivity using required x-ray hole-cutting technology available within OVERFLOW v2.2c
    - **Tested and applied x-ray logic extension to CGT script system developed at NASA JSC**
  - Replaced original user-generated box grids with OVERFLOW-generated off-body Cartesian grids (OFFBODY), and implemented near-body O-mesh strategy employed by NASA Ames on Trap Wing for the AIAA CFD High Lift Prediction Workshop (HiLiftPW-1)
    - **Removed all wakes (replaced wing trailing edge topology with O-mesh)**
    - **Grew all component meshes out a constant distance (zreg)**
    - **Set finest Cartesian mesh level explicitly (DS)**
  - Used *undivided second-difference of the Q vector** as the gradient sensor (other option is *vorticity*)

* Buning, P.G., and Pulliam, T. H., *"Cartesian Off-Body Grid Adaptation for Viscous Time-Accurate Flow Simulation,"* AIAA 2011-3693

Overset Grid Adaptation

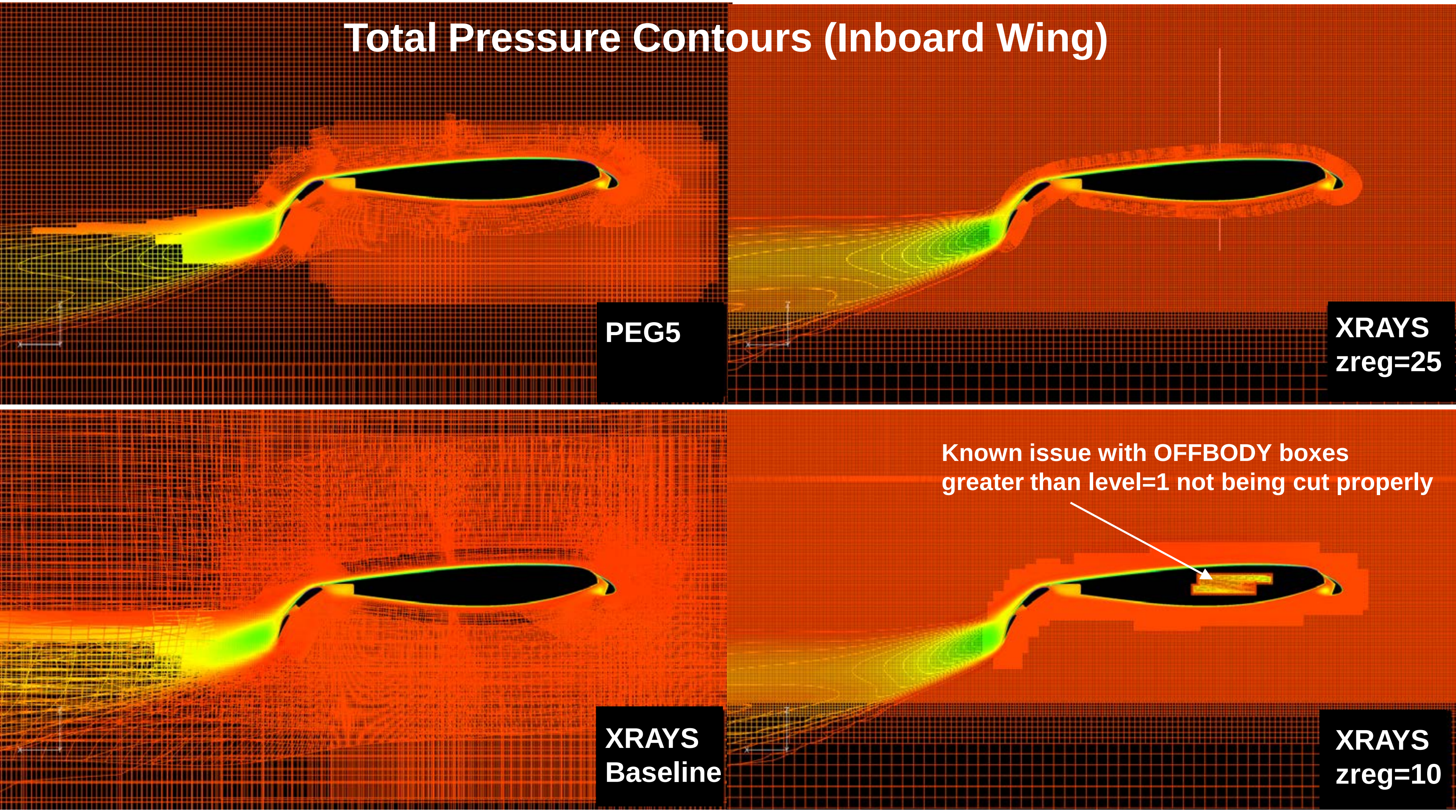
Evaluation of Off-Body Grid Adaptation for High-Lift

- **Mach=0.2, α=approach, WT Reynolds number, SA turbulence model, 3rd-order Roe upwind**
- **Test Cases:**
  - *peg5* – **original grid system using current PEG5 hole-cutting method**
  - *xrays zreg10* – **original near-body grids with outer boundaries at 10", OVERFLOW-generated OFFBODY grids with DS=1.0 (10% of zreg)**
  - *xrays zreg25* – **original near-body grids with outer boundaries at 25", OVERFLOW-generated OFFBODY grids with DS=2.5 (10% of zreg)**
  - *xrays zreg25 adapt25* – **original near-body grids with outer boundaries at 25", OVERFLOW-generated OFFBODY grids with DS=2.5 (10% of zreg), 8 cycles of adaptation every 25 iterations (200 total iterations) using default undivided second-difference sensor**

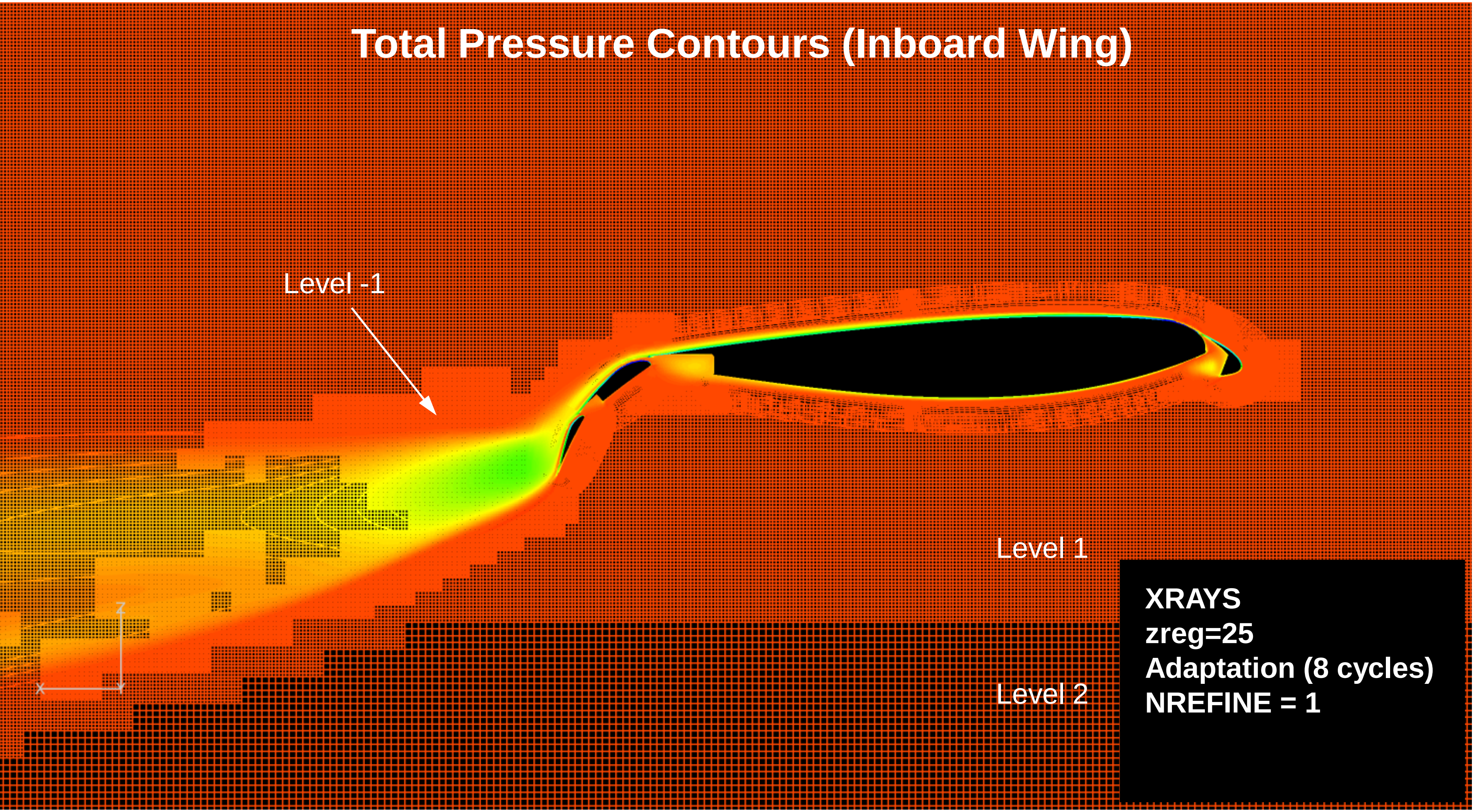
Name	Holecutting Method	Mach	ZREG	NREFINE	NADAPT	NSTEPS (During Adapt)	Grid Points (M)	Zones Total	Zones Near-Body	Zones Off-Body	Zones Adapt
peg5	PEG5	0.2					47.2	152			
xrays baseline	XRAYS	0.2					47.2	152			
xrays zreg25	XRAYS	0.2	25.0				89.5	698	150	548	
xrays zreg10	XRAYS	0.2	10.0				658.3	1404	150	1254	
xrays zreg25 adapt	XRAYS	0.2	25.0	1	25	200	218.9	4934	150	2027	2757

Overset Grid Adaptation

Evaluation of Off-Body Grid Adaptation for High-Lift



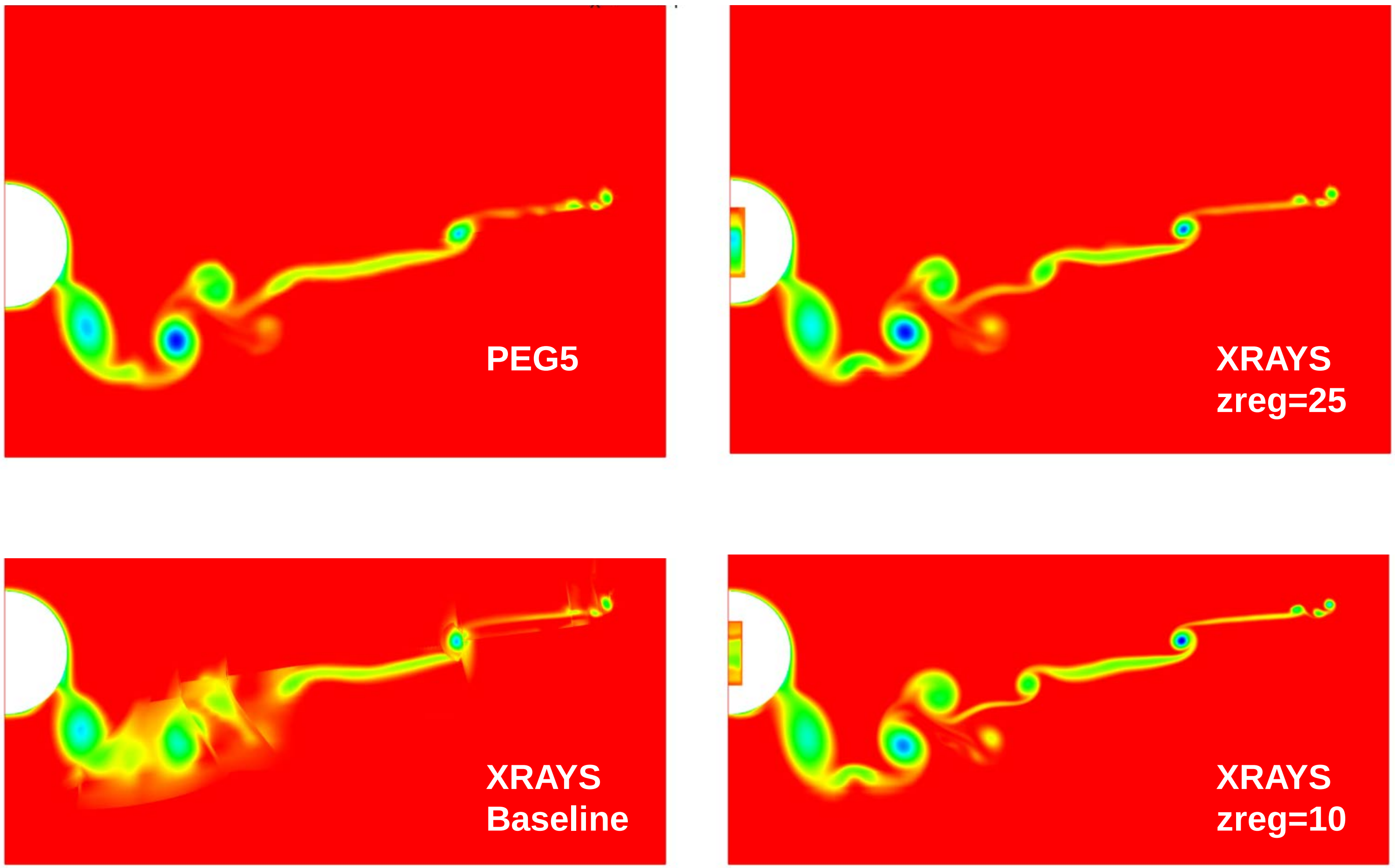
Overset Grid Adaptation
Evaluation of Off-Body Grid Adaptation for High-Lift



Overset Grid Adaptation

Evaluation of Off-Body Grid Adaptation for High-Lift

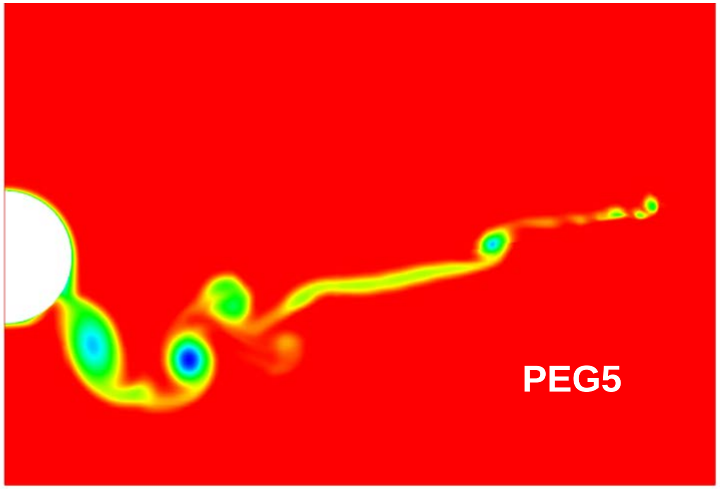
Total Pressure Contours (Downstream of wing)

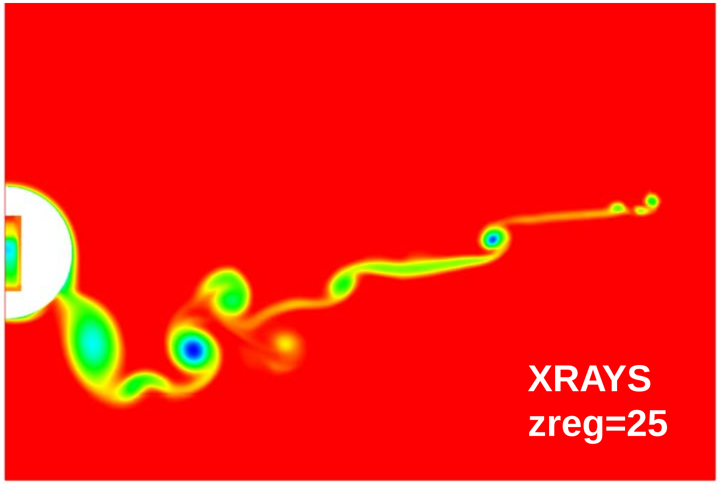


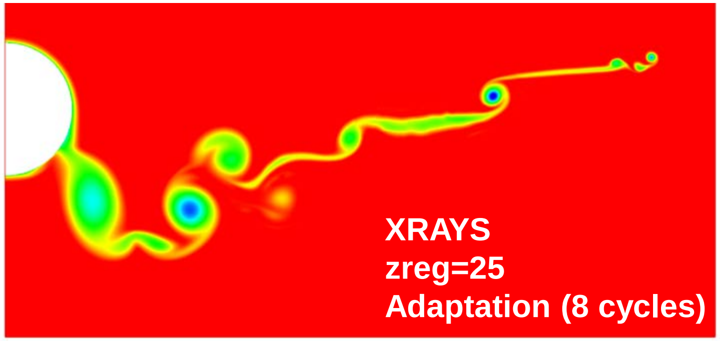
Overset Grid Adaptation

Evaluation of Off-Body Grid Adaptation for High-Lift

Total Pressure Contours (Downstream of wing)





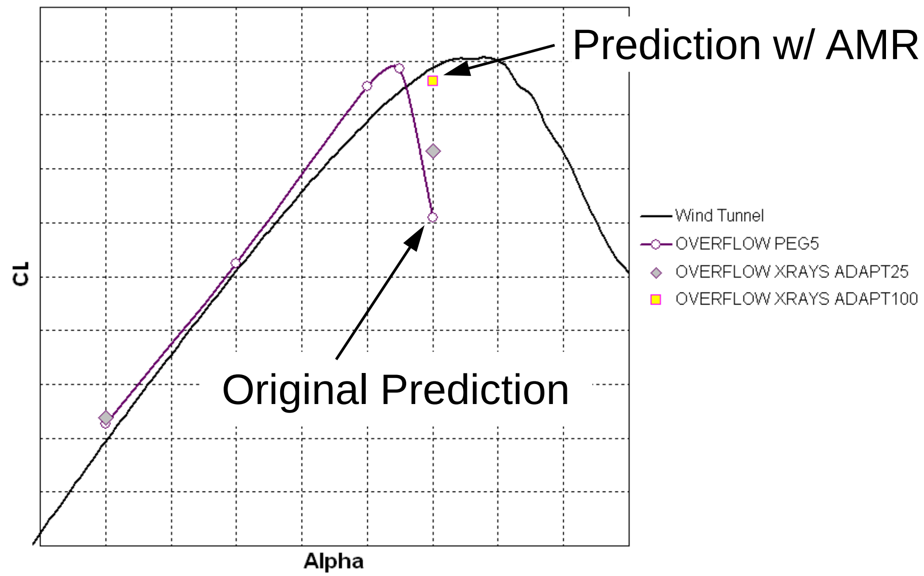


Overset Grid Adaptation

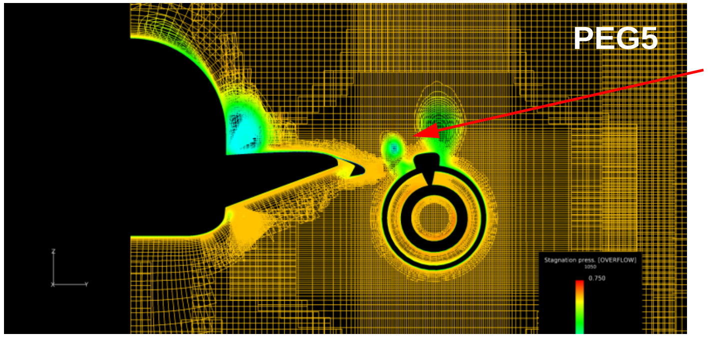
Evaluation of Off-Body Grid Adaptation for High-Lift

Engineering, Operations & Technology | **Boeing Research & Technology**

- **777-200 OVERFLOW simulations obtained near stall with and without AMR at higher α**
  - Baseline approach (PEG5) shows difference of >10% in lift with test data
  - 8 cycles of AMR (every 100 steps) yields difference of **<1%** in lift with test data

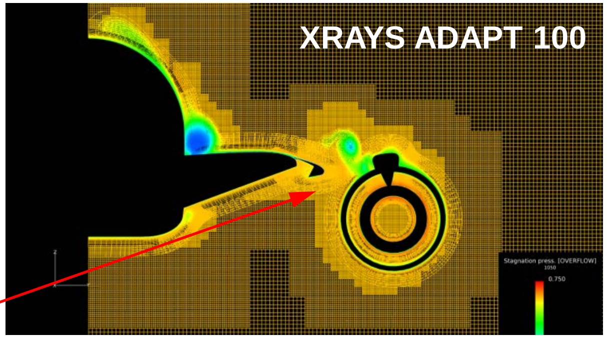


- **Off-body flow features significantly better resolved with AMR**



Not enough grid resolution to adequately resolve the chine vortex as it convects up and over the main wing

AMR automatically places isotropic Cartesian mesh cells in high gradient regions allowing for more accurate simulation of flow features



Overset Grid Adaptation

Evaluation of Off-Body Grid Adaptation for High-Lift

- **OVERFLOW AMR technology requires use of the X-ray method of overset grid mesh pre-processing**
  - As compared to the current PEGASUS 5 (PEG5) approach, the X-ray method is ~5X faster (GOOD!)
  - However, the amount of user manual intervention required to use the X-ray method is significantly more (~3-5X greater) than using PEG5 (NOT SO GOOD)

- **OVERFLOW AMR technology requires more computational resources to obtain a steady-state flow solution relative to the current overset grid CFD process:**

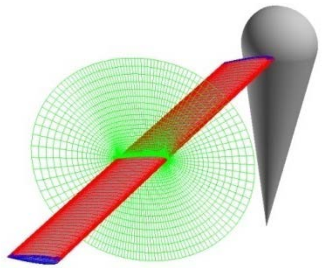
Name	Holecutting Method	ZREG	NREFINE	NADAPT	NSTEPS (During Adapt)	Final Iteration	Grid Points (M)	Zones Total	Zones Near-Body	Zones Off-Body	Zones Adapt	Clock Hours	Clock Speed Relative to PEG5
peg5	PEG5					20000	47.2	152				48.5	
xrays zreg25 adapt25	XRAYS	25.0	1	25	200	20000	120.1	2020	150	845	1025	84.3	1.7
xrays zreg25 adapt100	XRAYS	25.0	1	100	800	20000	188.8	4002	150	1509	2343	122.1	2.5

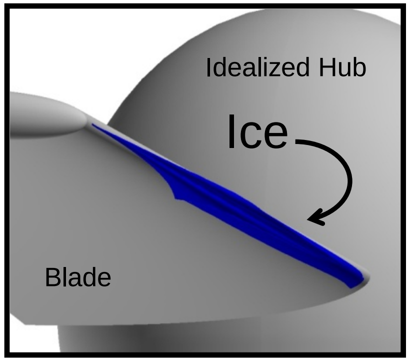
Selected OVERFLOW Applications

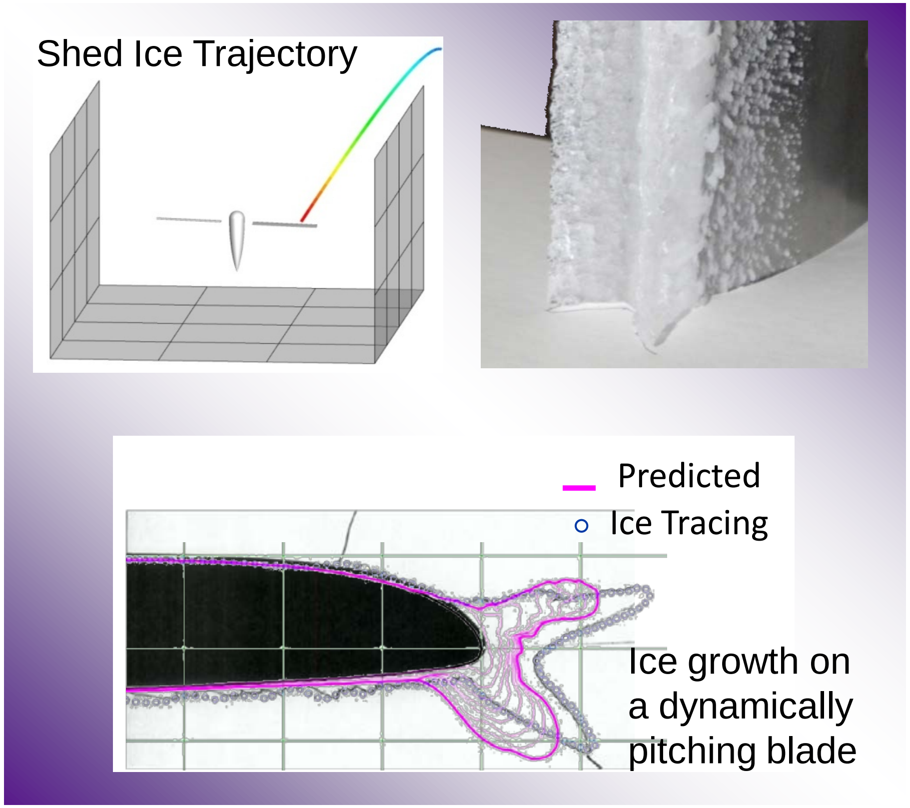
- **Rotorcraft**
- **Active Flow Control (AFC)**

Rotor Icing Analyses with OVERFLOW

OVERFLOW is loosely coupled with LEWICE3D to support ice growth performance degradation, and shedding analysis for rotor systems







The rotor processes and analyses were funded by the Vertical Lift Consortium, formerly the Center for Rotorcraft Innovation and the National Rotorcraft Technology Center (NRTC), U.S. Army Aviation and Missile Research, Development and Engineering Center (AMRDEC) under Technology Investment Agreement W911W6-06-2-0002, entitled National Rotorcraft Technology Center Research Program. The authors would like to acknowledge that this research and development was accomplished with the support and guidance of the NRTC and VLC. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the AMRDEC or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation thereon.

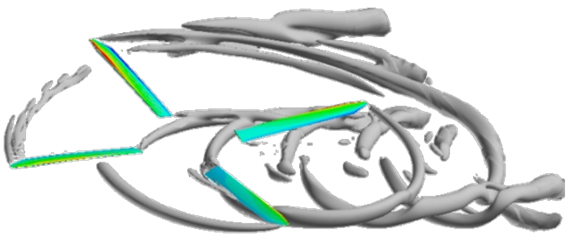
NRTC/VLC Project: ***High Fidelity Icing Analysis and Validation for Rotors*** **(WBS No. 2012-B-11-T1.1-P2)**

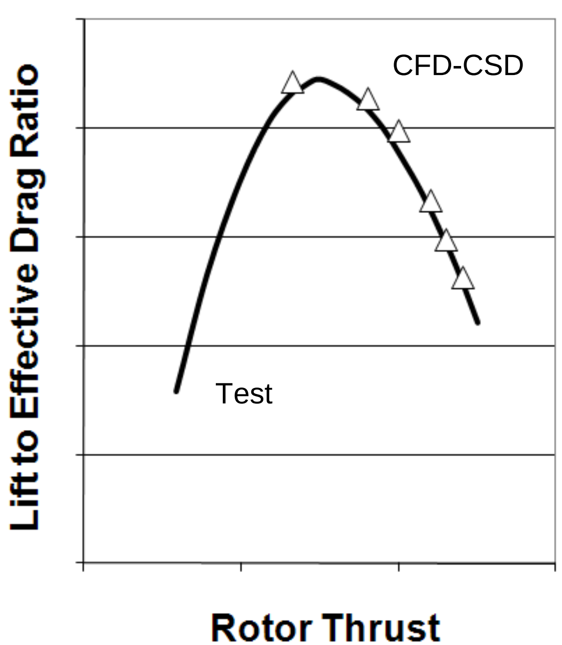
Application of Coupled CFD-CSM to Rotor Design for Performance and Loads

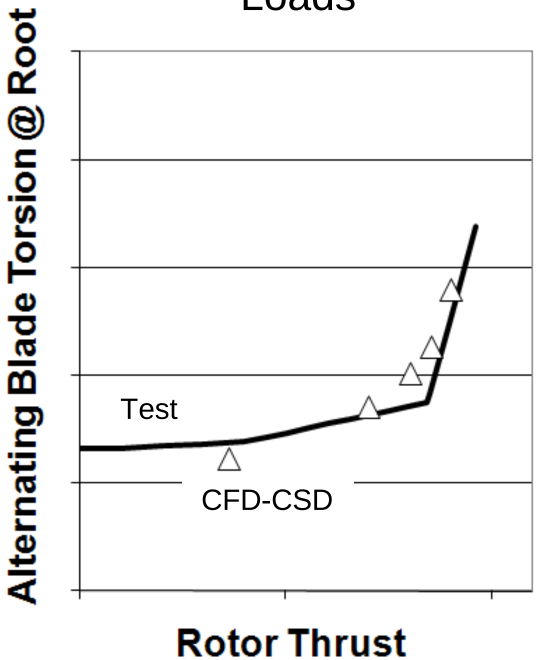
Engineering, Operations & Technology | **Boeing Research & Technology**

- CFD airloads on the 6-DOF elastically deforming rotor are computed and communicated to CSD for full aircraft trim and dynamics response.

Boeing Model 360 Coupled OVERFLOW-RCAS Codes







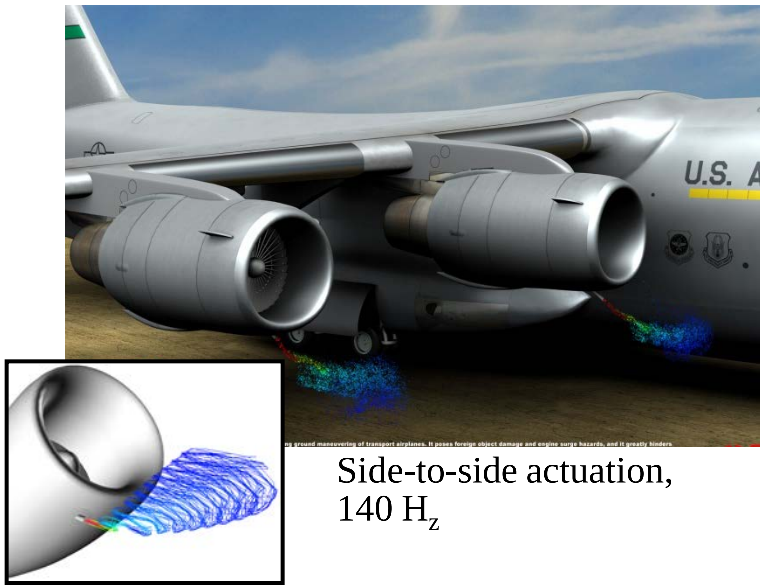
The rotor processes and analyses were funded by the Vertical Lift Consortium, formerly the Center for Rotorcraft Innovation and the National Rotorcraft Technology Center (NRTC), U.S. Army Aviation and Missile Research, Development and Engineering Center (AMRDEC) under Technology Investment Agreement W911W6-06-2-0002, entitled National Rotorcraft Technology Center Research Program. The authors would like to acknowledge that this research and development was accomplished with the support and guidance of the NRTC and VLC. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the AMRDEC or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation thereon.

NRTC/VLC Project: ***Design for Performance and Loads using CFD/CSD in Advanced Rotor Concepts*** **(WBS No. 2009-B-01-02.1-P2)**

Active Flow Control Applications

- **Objective: Alleviate ground vortex ingestion**
  - New AFC approach: “Sprinkler system”

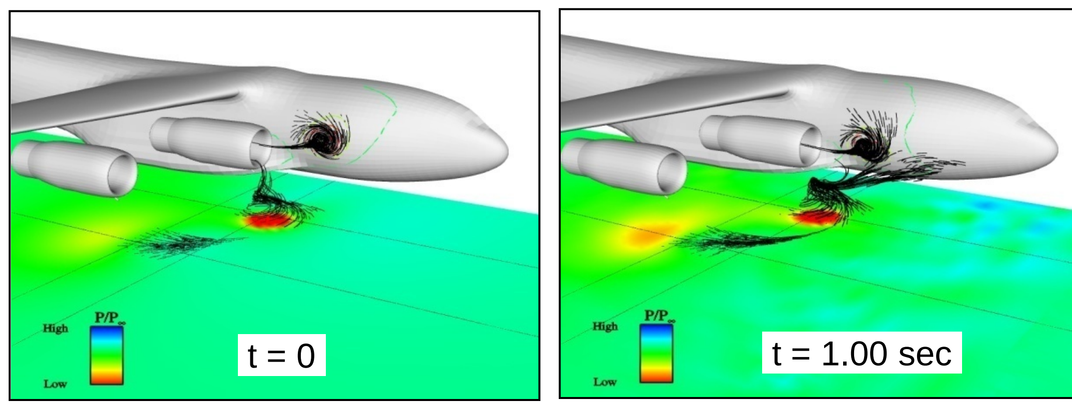
Short Time-Scale Flow Development



Side-to-side actuation,
140 H_z

- *In real-life operations the vortex is unsteady*
- *Control method has to address the unsteady characteristics of realistic flows*

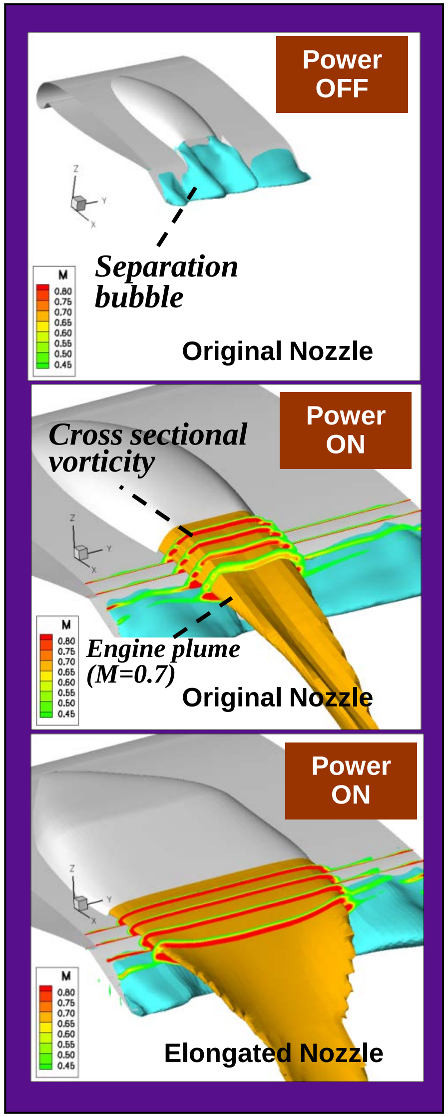
Long Time-Scale Flow Development



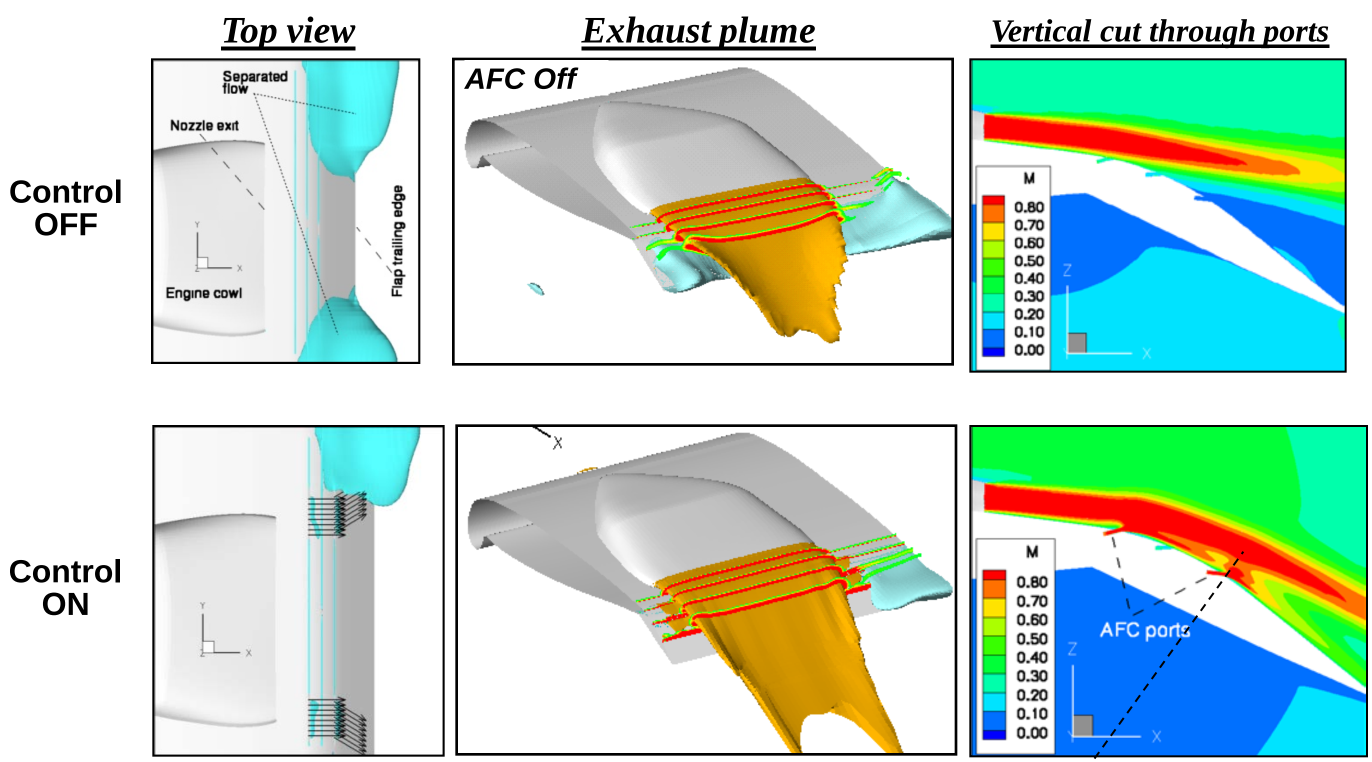
Periodic scanning over wide area effectively eliminates ground vortex

Reference: “Flow Control Techniques for Transport Aircraft”,
A.Shmilovich, Y.Yadlin AIAA Journal, 2011, Vol.49: 489-502

Active Flow Control Applications



- **Objective: Develop technologies for more effective STOL**
  - Enhanced Coanda effect of the USB system
  - New AFC approach for the high-lift system
  - Actuation results in increased USB effectiveness



Higher exhaust turning results in increased circulation

Concluding Remarks

- **Boeing relies heavily on overset grid CFD methods to design and analyze virtually all of the air and space vehicles we build.**

- **Because this technology is so important to us, we have invested, and continue to invest, in the development of tool and process improvements and application validation.**

- **Concurrently, we remain active in the overset CFD community, and work to share and leverage as much externally developed technology as possible.**
  - We truly appreciate the incredible amount of technology that is currently being developed within the overset CFD community, and particularly at NASA.
  - We have been, and will remain, open to collaborating with external organizations in a mutually beneficial manner to advance the state-of-the-art in overset CFD technology.

BOEING