High-Order Overset CFD Simulations Using FDL3DI

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- Most of the research performed using FDL3DI is conducted under the sponsorship of AFOSR

OUTLINE

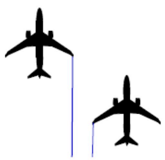
- Organizational Overview
- Overview of FDL3DI
- Recent upgrades of FDL3DI
  - “FDLv2”
  - BUNGe Domain Decomposer
- Three Recent Applications of FDL3DI
  - Wing-Vortex Aerodynamics
  - Flow control for laminar flow airfoils
  - Shock/boundary layer interaction in front of canonical shapes

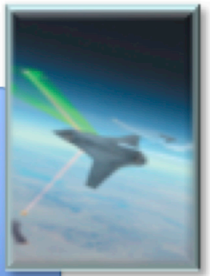
MULTI-DISCIPLINARY AERODYNAMICS TEAM

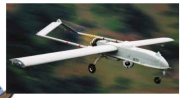
Research Scope

Overarching Framework

More Energy Efficient, Capable and Sustainable Solutions for ISR, Mobility, Future Air Dominance

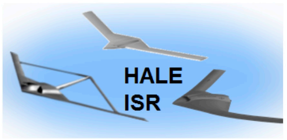






Solution Space

- Laminar Flow
- Unconventional Configurations
- DE/KE weapon integration
- Formation Flight
- Lightweight Structures
- Quiet SUAS's
- Novel Flow Control



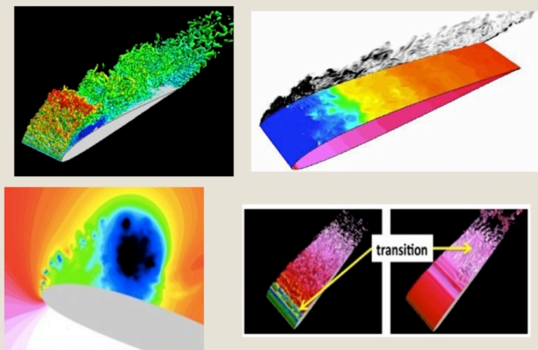
Complex Multi-Disciplinary Physics

- Vortex/Surface Interactions, Buffeting & Flutter
- Gust Response & Unsteady Separation
- Transition
- Compressibility Effects
- Coupling of Transition Excursions with Aeroelastic Response
- Complex Flow-Acoustic-Structural Interactions
- Fluid-Optic Interactions

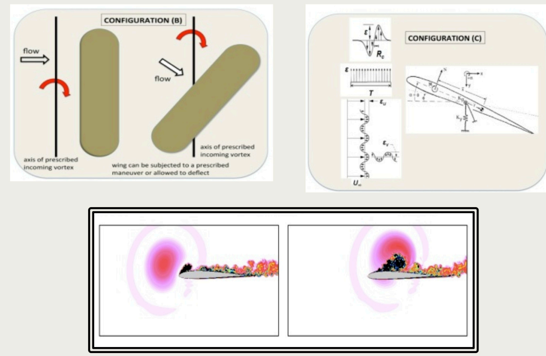
Multi-disciplinary Aerodynamics Team

Research Scope

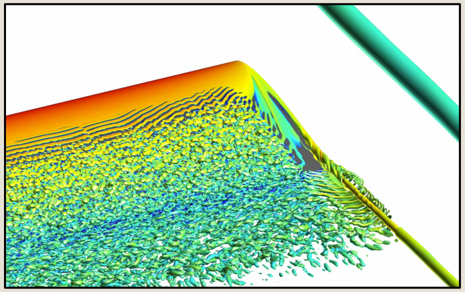
Dynamic Stall at Higher Re



Wing-Gust Interactions

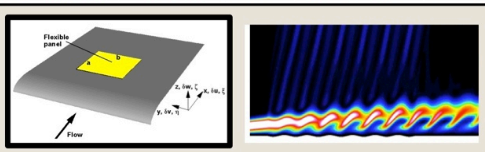


Streamwise-oriented Vortex-Wing Interactions

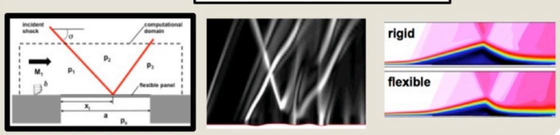


Response of Flexible Panels

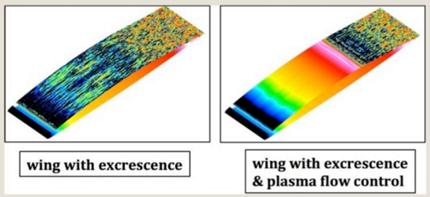
Coupling of transition with surface deformation



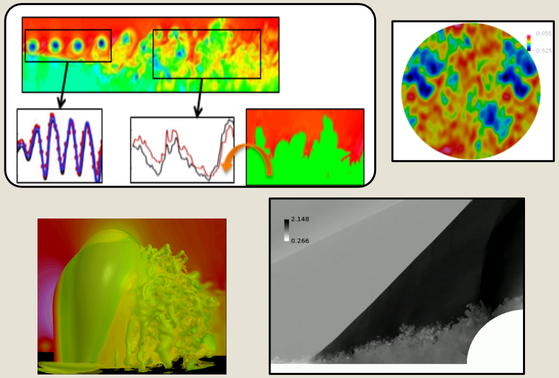
Shock impingement



Plasma-based control of Transitional Flows

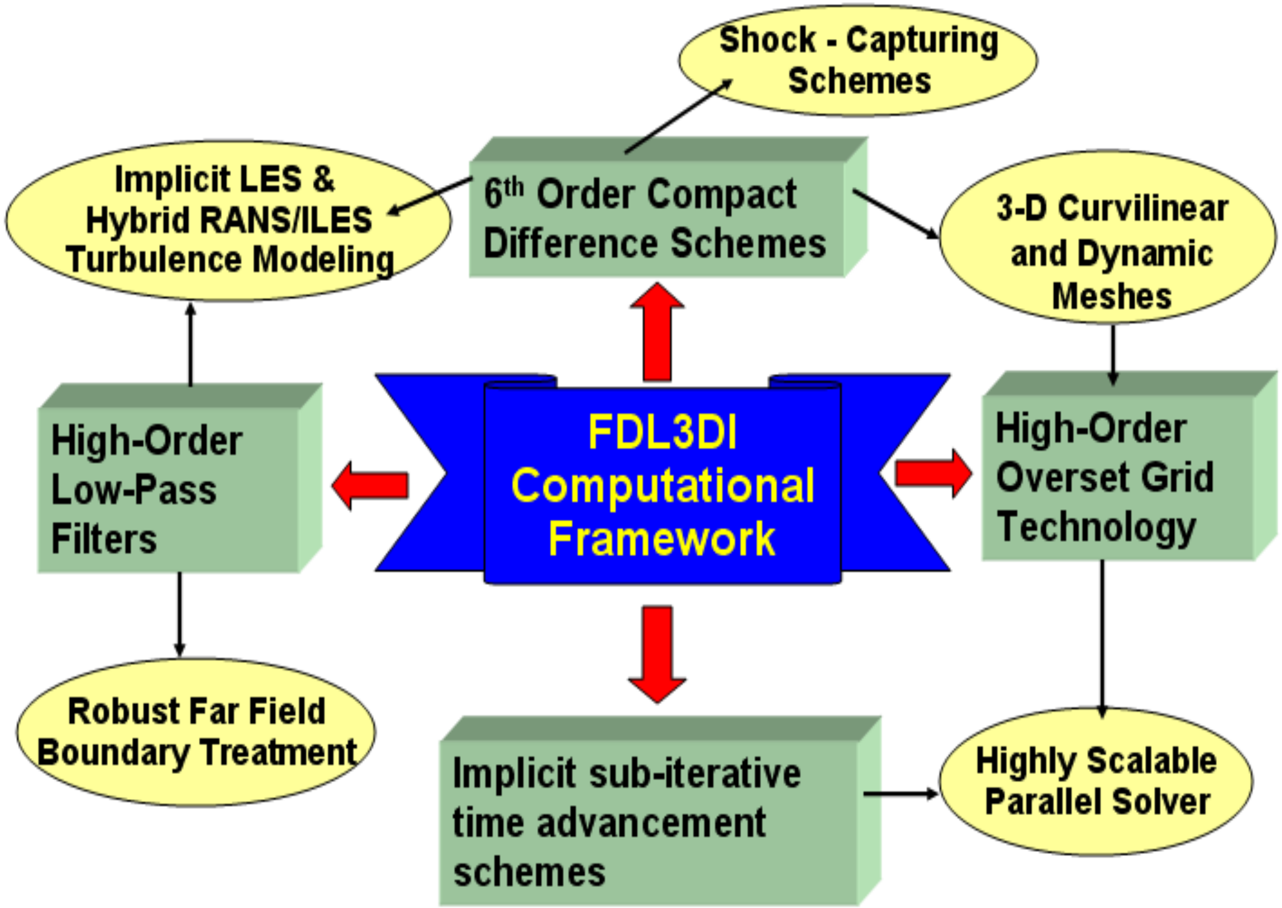


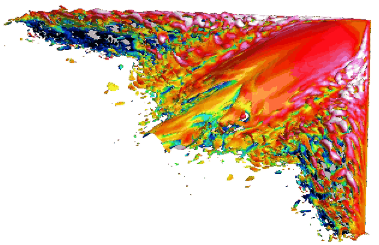
Aero-optics

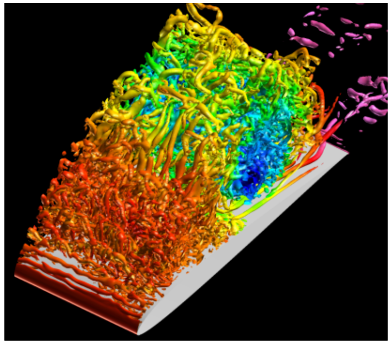


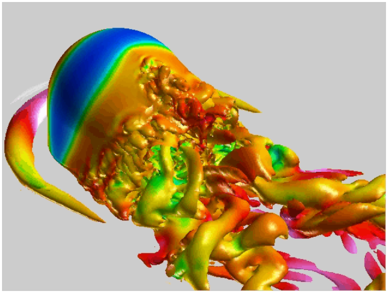
FDL3DI OVERVIEW

High-Fidelity Computational Framework



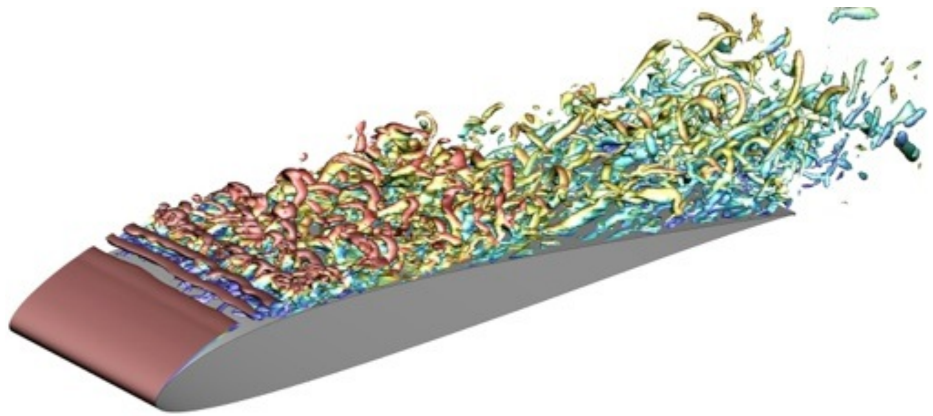






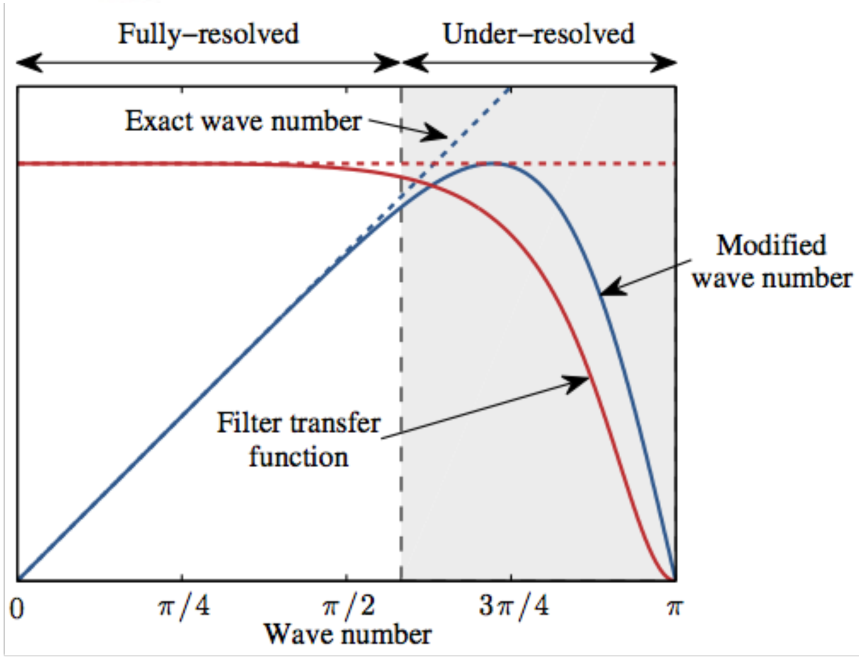
NUMERICAL APPROACH

Implicit LES Technique



Challenges

- Accurate transition prediction
- Interspersed regions of laminar/transitional/ turbulent flows
- Extendable to dynamic problems and realistic geometries



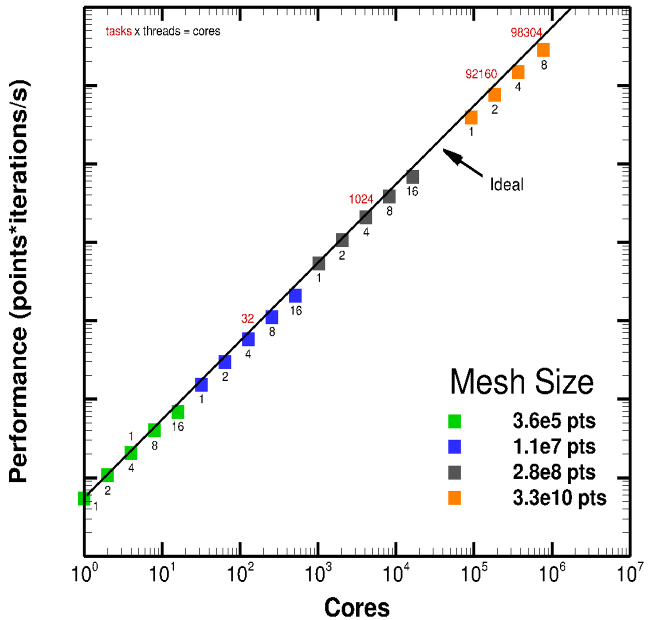
High-fidelity Implicit LES approach

- Accuracy provided by 6th-order compact finite differencing
- A high-order filter acts as an implicit subgrid-stress (SGS) model
- Provides a seamless approach for mixed laminar/transitional/turbulent flows
- Has been extensively-validated for benchmark and applied problems

FDL3DI: ILES flow solver

Recent Improvements to FDL3DI

"FDLv2"



Converted entire code to Fortran90

- A modular design, use of allocatable arrays, etc.
- Placed under version control using git
- Strong portability…no external libraries
- General code clean-up for consistency, readability and cache/vectorization improvements

MPI-I/O

- Orders of magnitude increase in I/O speed
- Dramatically reduces processor idle time in I/O
- Enables significantly larger problems

OpenMP multi-threading

- Proven linear scalability decreases runtime while retaining solution quality
- Facilitates simulation of more relevant flow conditions with practical runtime

Robust hole-cutting and scheme adaption

- Enables more complex and aircraft-relevant configurations
- A shock detection and capturing capability with dynamic scheme adjustment (Compact/ Roe hybrid, adaptive filtering, or selective artificial dissipation)

Algorithmic enhancements via filter compact delta formulation

- Drastic simplification of the code...removed thousands of redundant lines of code
- Permits adaptive filtering and on-the-fly scheme adjustments for future capabilities

Recent Improvements to FDL3DI

Previous Approach vs Current Approach

Previous Approach = BELLERO + FDL3DI

- Run PEGASUS to get second-order, grid-level connectivity
- Run BELLERO to process Plot3D grid and XINTOUT file
  - Determine “optimum” grid decomposition
  - Establish point-to-point connectivity for block-level (decomposed) topology and handle periodic boundary conditions
  - Decompose grid-level connectivity obtained from PEGASUS to block level
  - Compute high-order offsets / interpolation coefficients using expanded stencils
  - Track hole boundaries for insertion of appropriate one-sided derivative and filter formulations in neighborhood of holes
  - Write out high-order XINTOUT file (plus additional data in auxiliary files)
- Run FDL3DI using input files generated by BELLERO

Useful but limitations became apparent over time

- A lack of robustness in grid decomposition algorithm
- Code executed serially with considerable redundancy (count/store loops)
- Source code overly complicated, not robust and difficult to maintain
- Large amount of serial file I/O, with BELLERO computing and writing out data (serially) to be subsequently read in (serially) by FDL3DI

RECENT IMPROVEMENTS TO FDL3DI

PREVIOUS APPROACH VS CURRENT APPROACH

Current Approach = BUNGe + FDLv2

(BUNGE: *B*ELLERO *U*pgrade for the *N*ext *Ge*neration)

- Run PEGASUS to get second-order, grid-level connectivity
- Run BUNGe to establish partition with improved methodology, using Plot3D grid file or just the grid header data if no holes are present
- All other BELLERO functionality has been absorbed by FDLv2
  - Communications updates are segregated by type (P2P, periodic, overset)
  - Expansion of stencils to high-order simplified and more robust
  - Use of persistent MPI communication removes unnecessary handshakes for repeated non-blocking communication
  - Use of MPI sub-array datatypes removes unnecessary buffer copies
  - Extends efficient MPI scalability beyond 10,000 processors

Significant improvements in robustness and efficiency

- Marked increase in robustness and speed of partitioning with BUNGe
- BELLERO serial operations parallelized and streamlined within FDLv2 (each processor handles its own connectivity data)
- Source code simplified, improving readability and maintainability
- Minimized file I/O requirements, FDLv2 uses MPI-IO to read in original PEGASUS XINTOUT file (in addition to grid/restart files)

BUNGe – "Brute Force Done Smartly"

- Explore every possible partition given number of grids in original system and number of decompositions desired
- Code starts with a "preferred partition" and spirals outward using an efficient recursive algorithm trying to account for all possible partitions
- User can limit the range of blocks away from preferred partition to check, set upper time limit spent looking for a partition, or "success" criteria
- Code quickly eliminates unrealizable decompositions for a given grid, greatly reducing the number of partitions that have to be checked
- Many optimized metrics have been coded, haven't settled on "best"

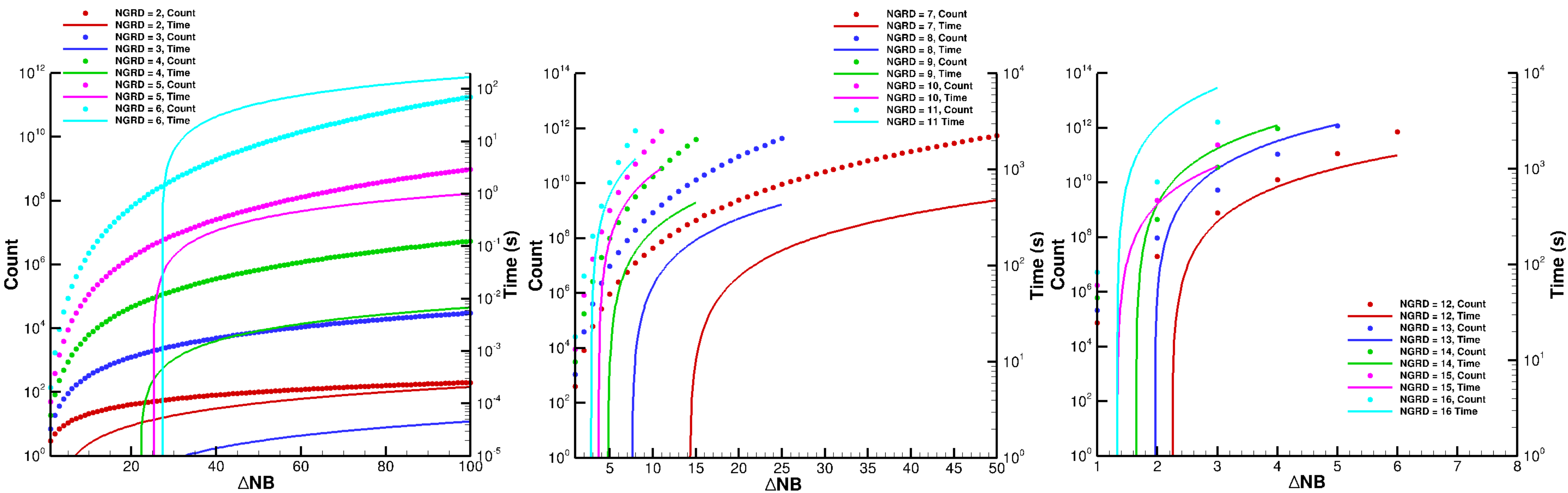
Strengths and Limitations

- Appears to be very efficient, fast and robust (although still serial)
- Allows user to explore range of decompositions before running solver
- Not currently "hole aware"…putting in this capability now
- Outstanding for grid systems with small numbers of grids, upper practical limit for number of grids in the original system (17 grids largest system decomposed thus far)

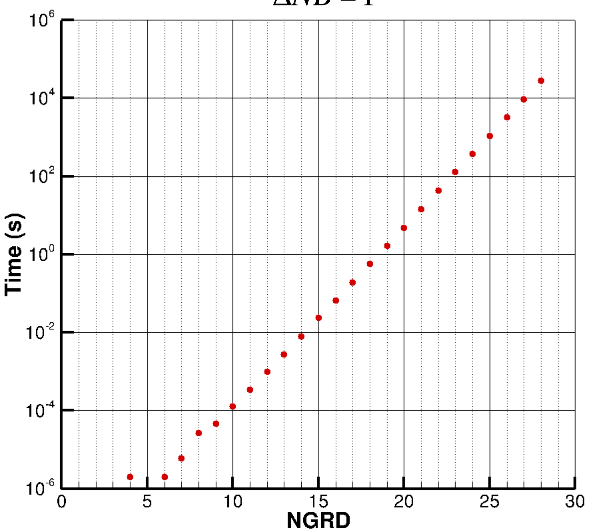
$$NP_{check} = \prod_{i=1}^{NG} (NB^i_{\max} - NB^i_{\min} + 1)$$

Recent Improvements to FDL3DI

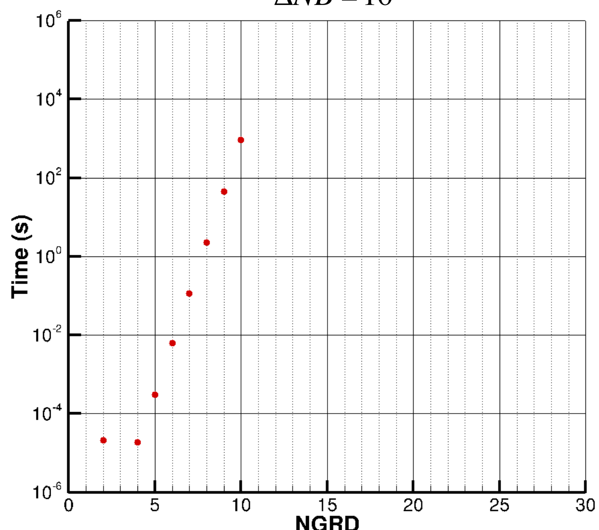
BUNGe Grid Partitioner



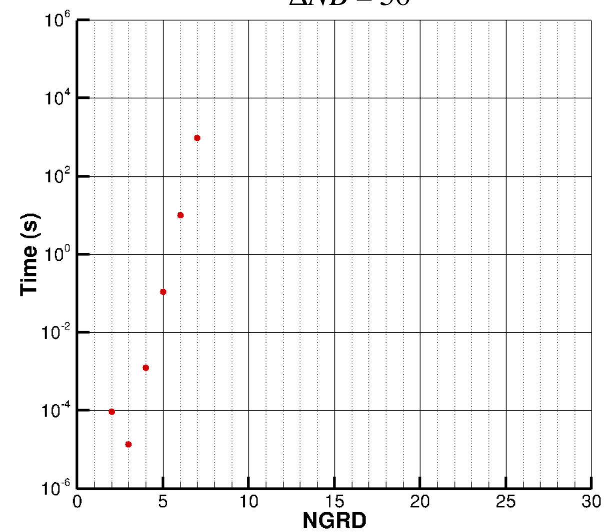
$\Delta NB = 1$



$\Delta NB = 10$



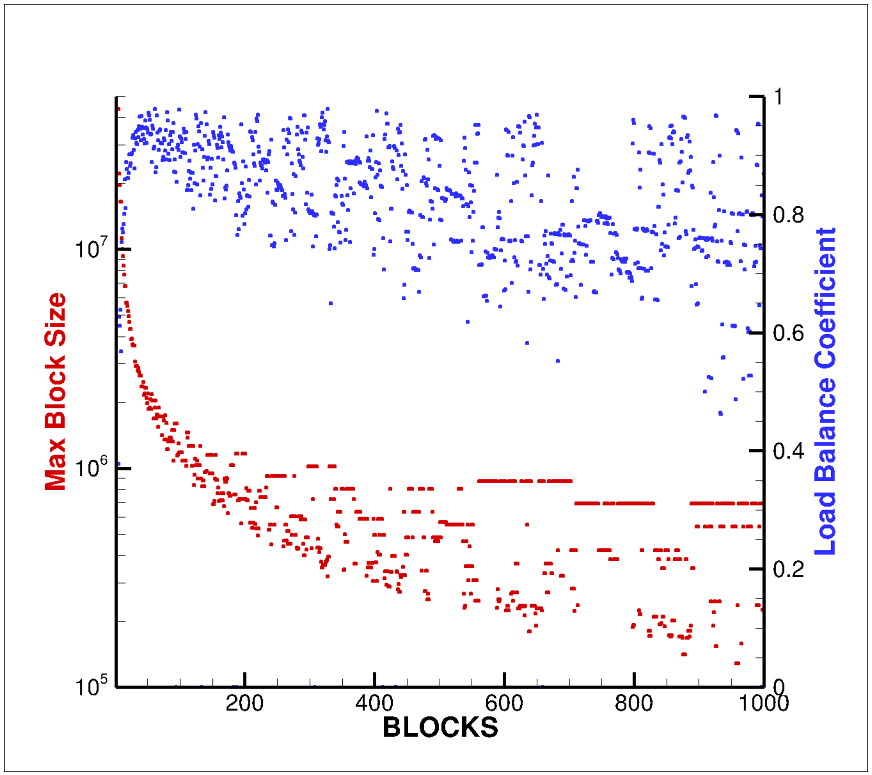
$\Delta NB = 50$

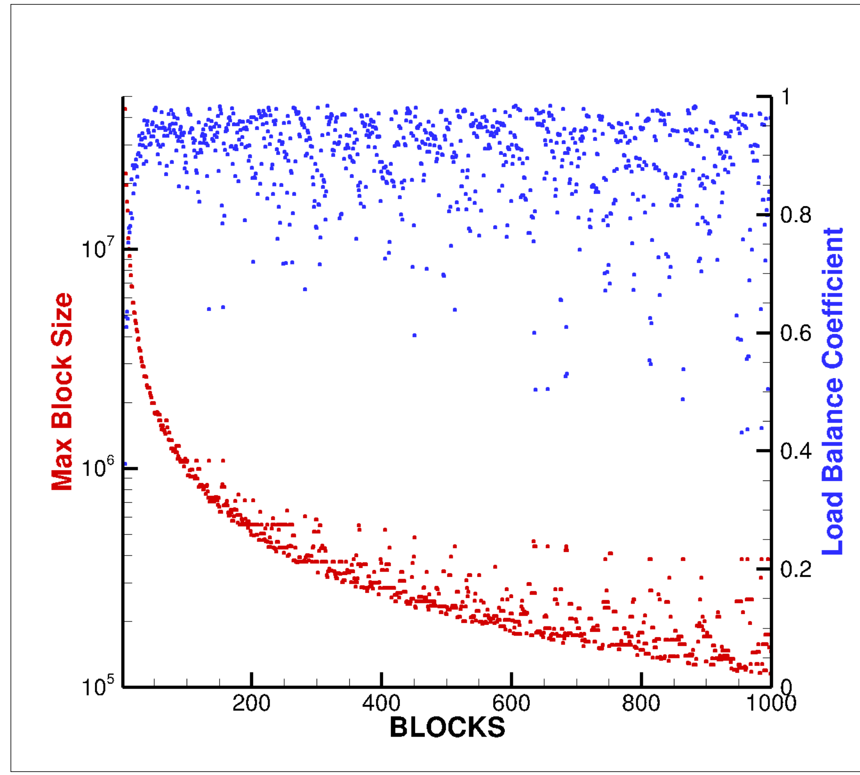


RECENT IMPROVEMENTS TO FDL3DI

FIVE-GRID TEST PROBLEM

ORIGINAL BELLERO





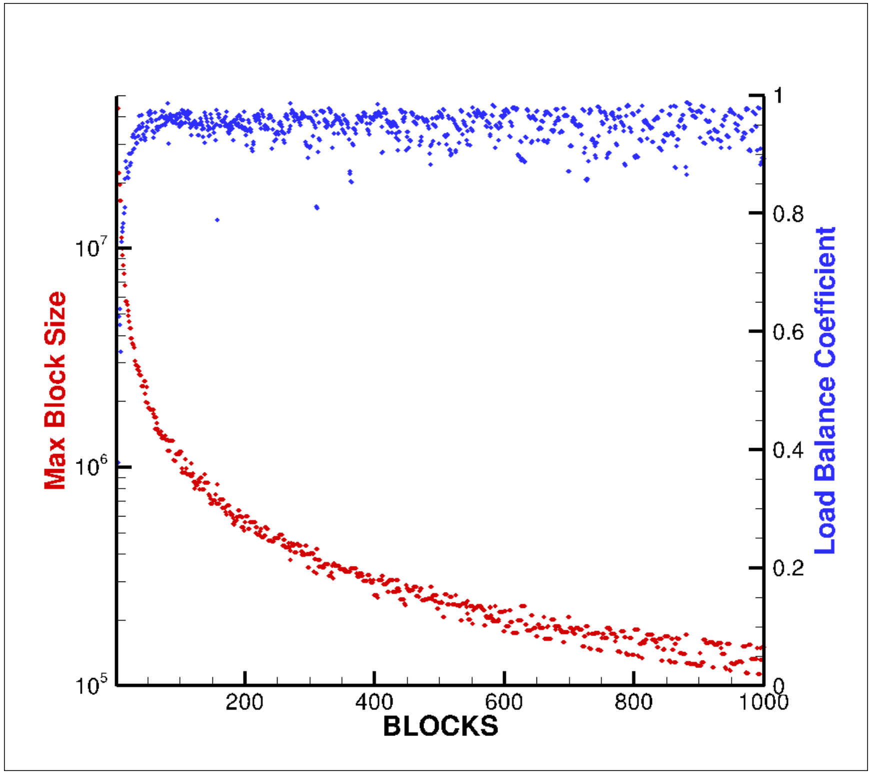
OPTIMIZED FOR "EFFICIENCY"
(MAXIMUM LOAD COEFFICIENT)

OPTIMIZED FOR "SPEED"
(MINIMUM MAX BLOCK SIZE)

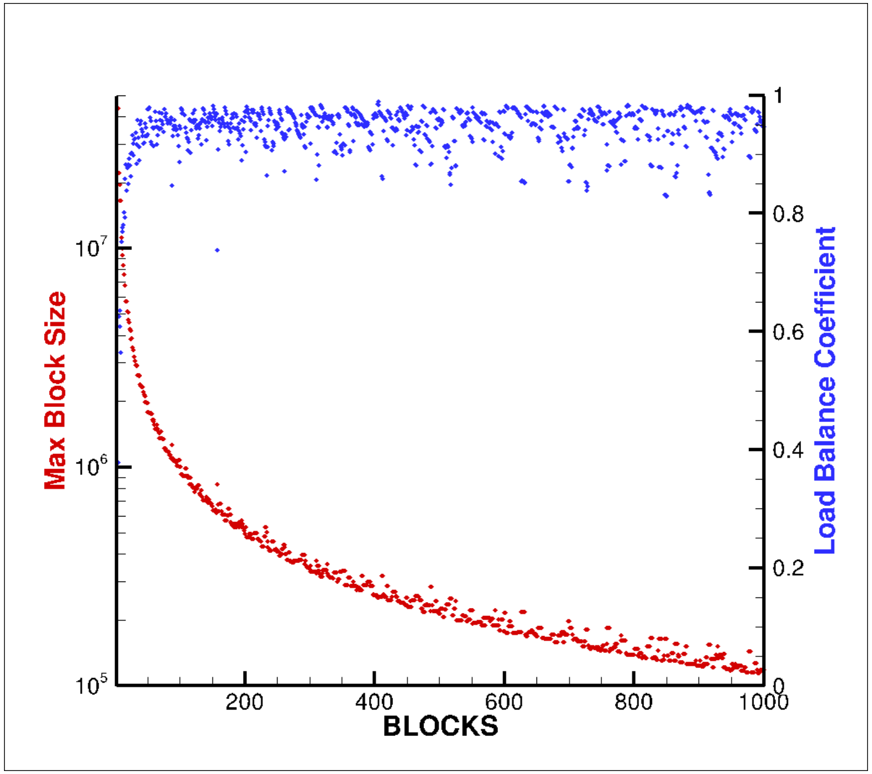
Recent Improvements to FDL3DI

Five-grid Test Problem

ΔNB = 1



Optimized for "Efficiency"
(Maximum load coefficient)

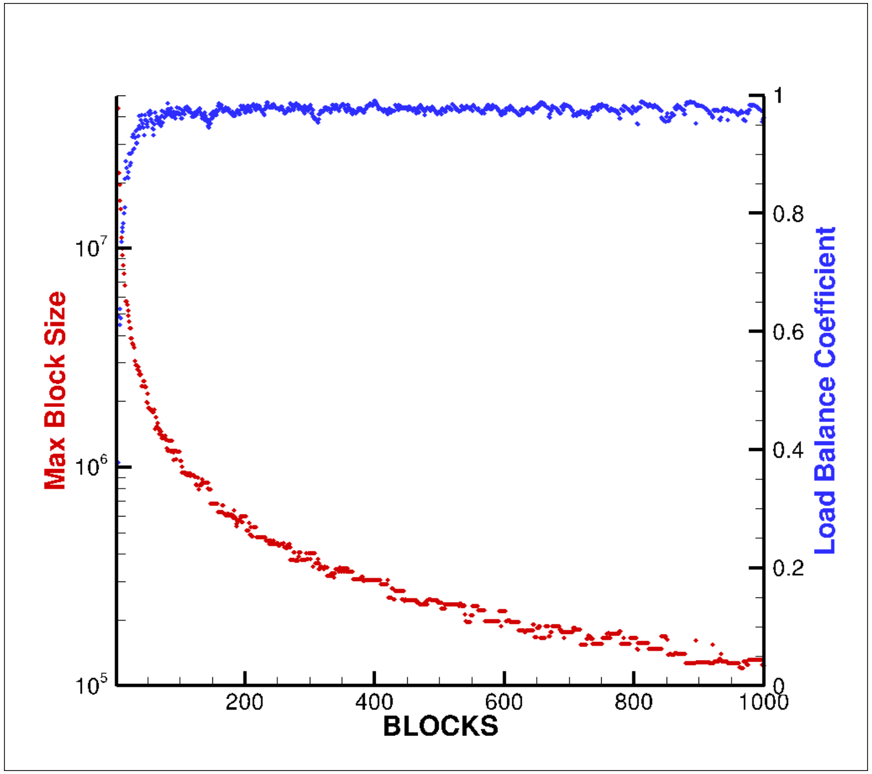


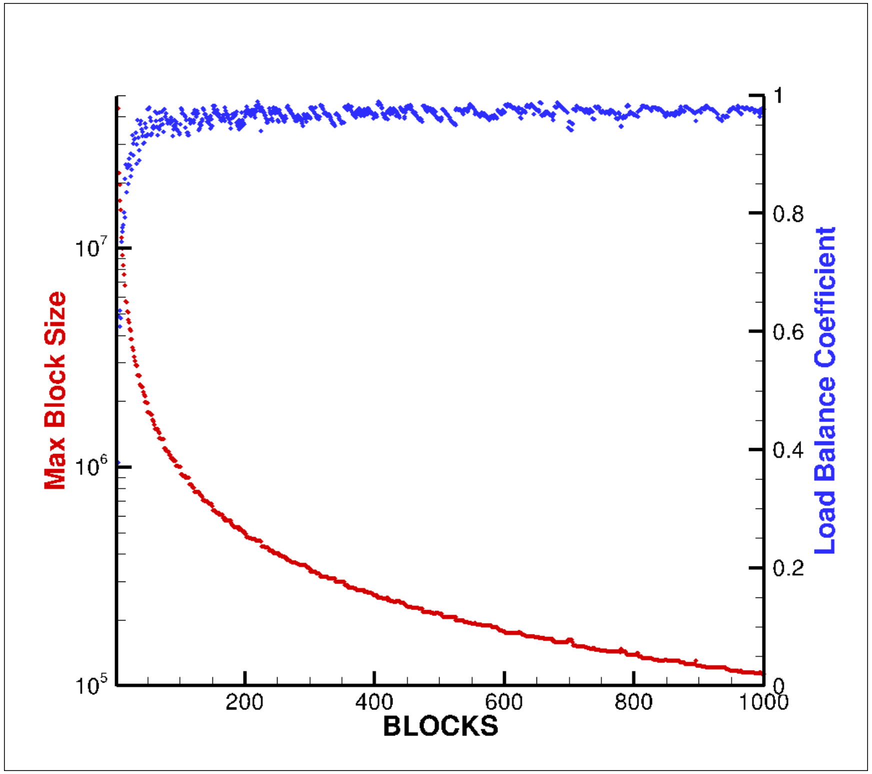
Optimized for "SPEED"
(Minimum Max Block Size)

Recent Improvements to FDL3DI

Five-grid Test Problem

ΔNB = 5





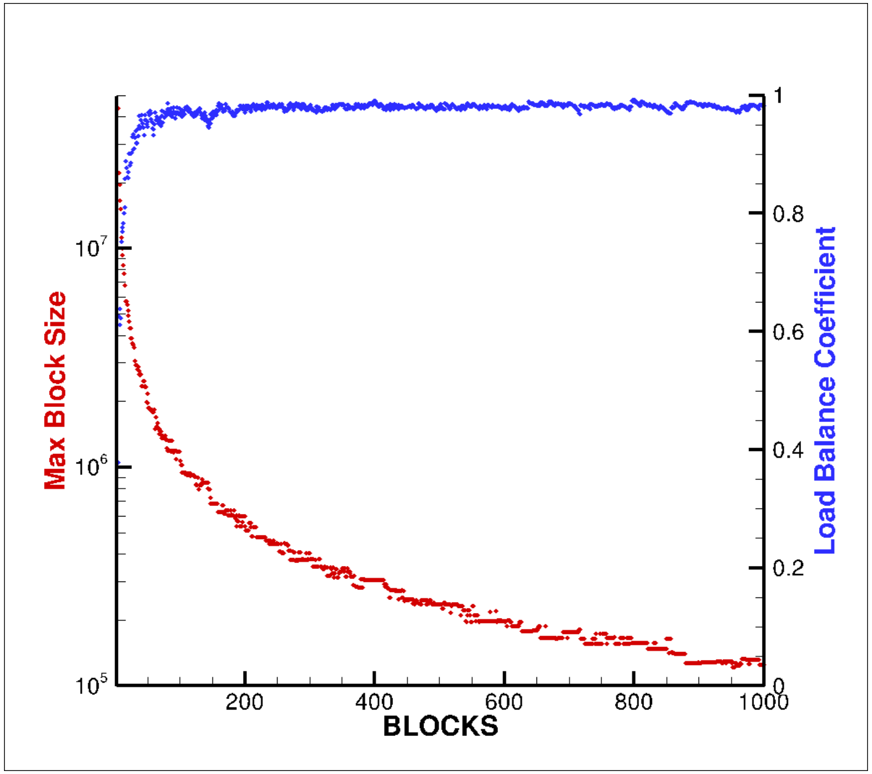
Optimized for "Efficiency"
(Maximum load coefficient)

Optimized for "SPEED"
(Minimum Max Block Size)

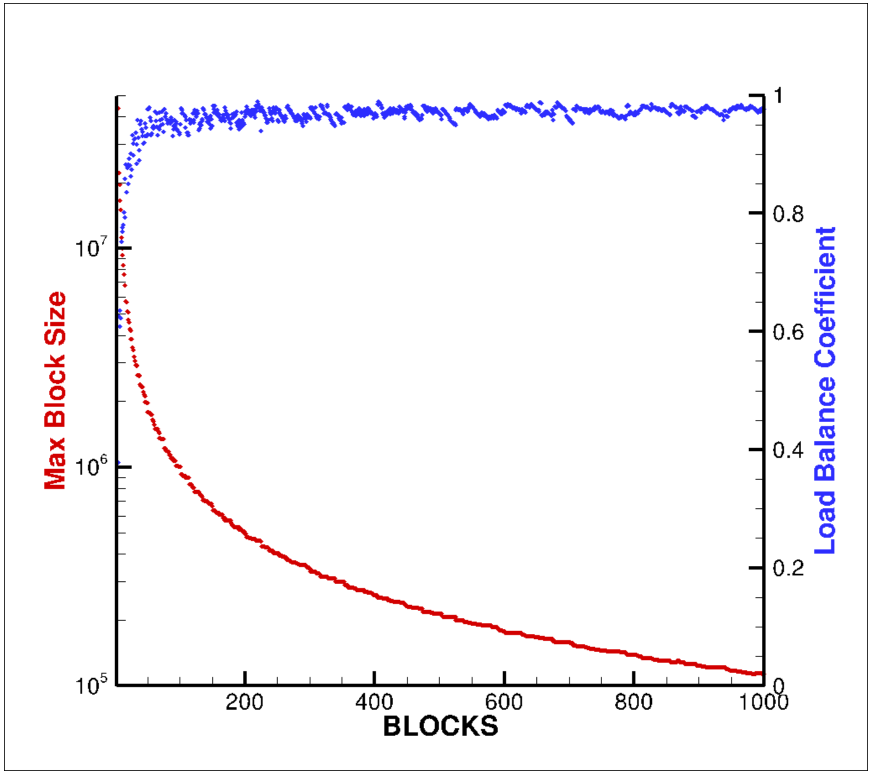
Recent Improvements to FDL3DI

Five-grid Test Problem

ΔNB = 10



Optimized for "Efficiency"
(Maximum load coefficient)

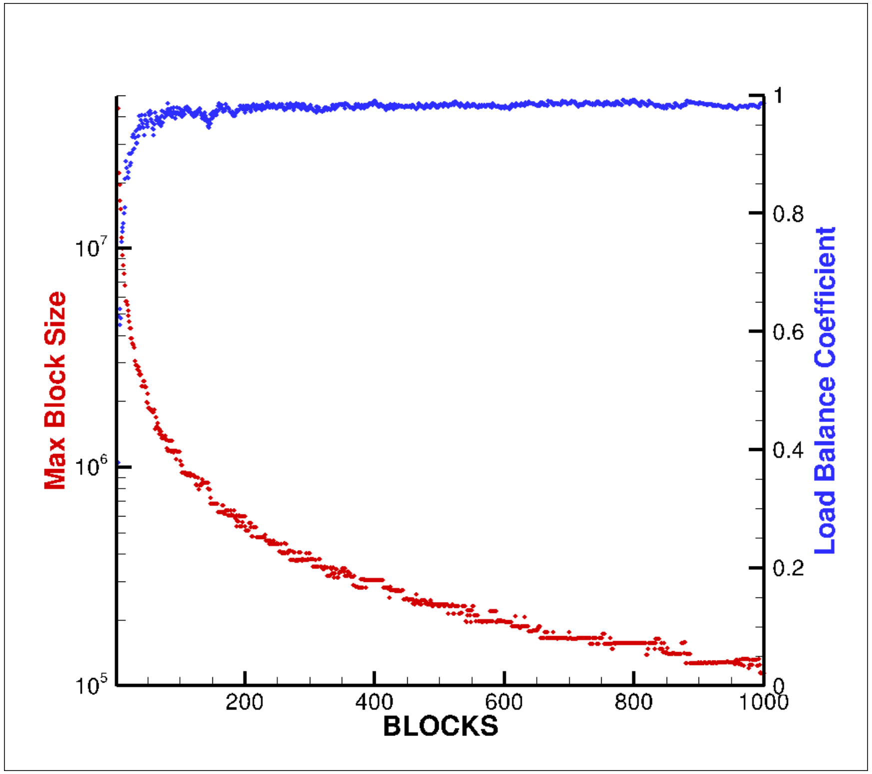


Optimized for "SPEED"
(Minimum Max Block Size)

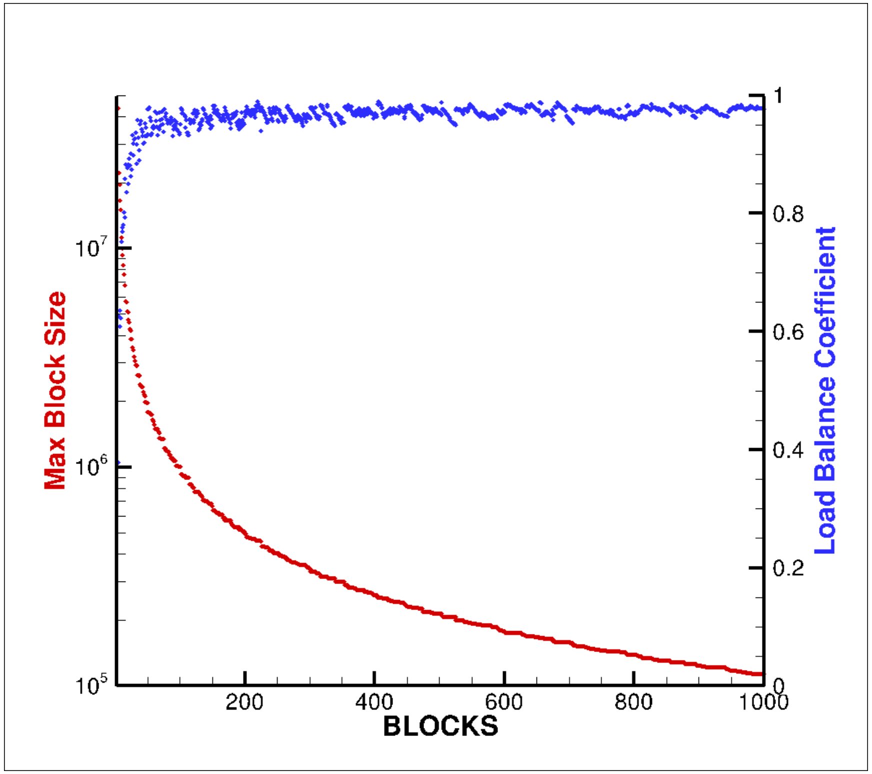
Recent Improvements to FDL3DI

Five-grid Test Problem

ΔNB = 25



Optimized for "Efficiency"
(Maximum load coefficient)

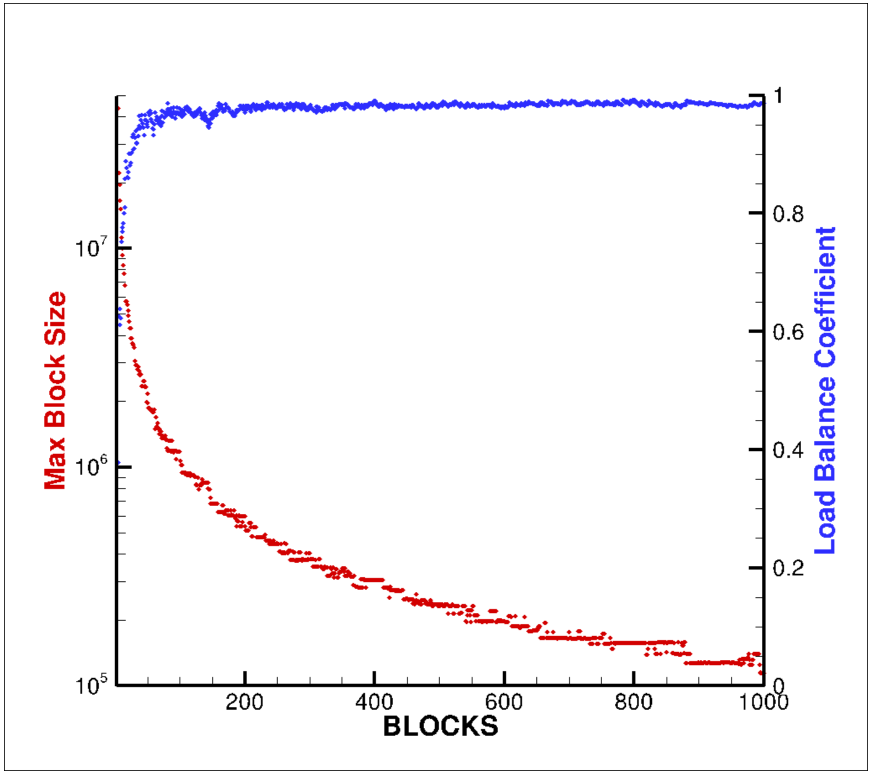


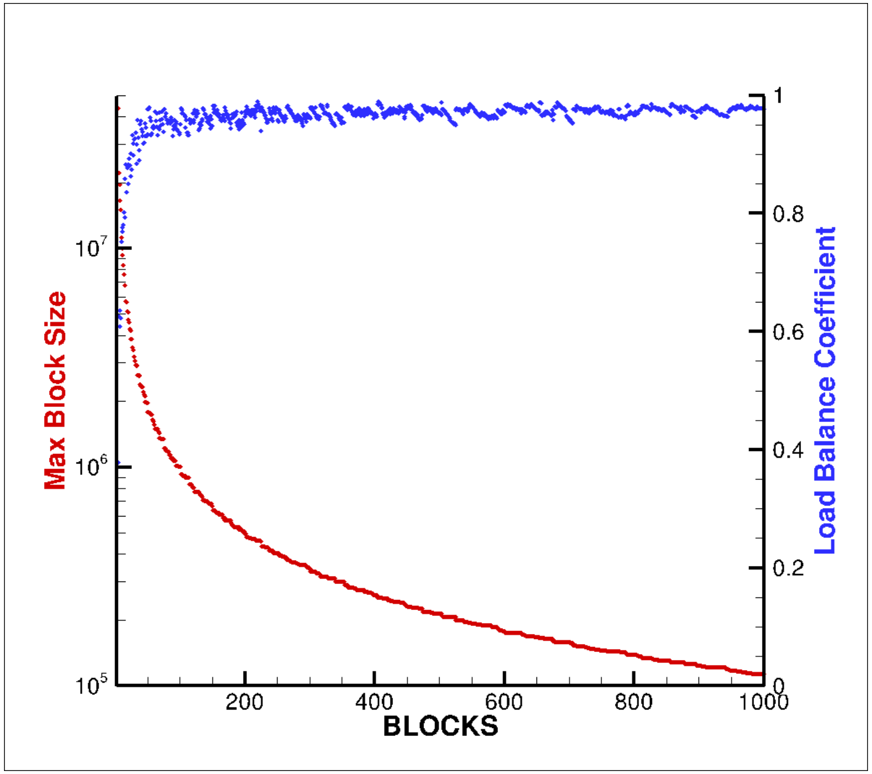
Optimized for "SPEED"
(Minimum Max Block Size)

Recent Improvements to FDL3DI

Five-grid Test Problem

ΔNB = 50





Optimized for "Efficiency"
(Maximum load coefficient)

Optimized for "SPEED"
(Minimum Max Block Size)

REPRESENTATIVE APPLICATIONS

Wing-Vortex Aerodynamics

- Unsteady evolution of tip vortex on stationary and oscillating wing
- Interaction of wing and streamwise oriented vortex

Flow Control for Laminar Flow Airfoils

- Plasma-based control of transition due to leading-edge excrescence
- Continuous, pulsed and segmented blowing for high-lift configuration

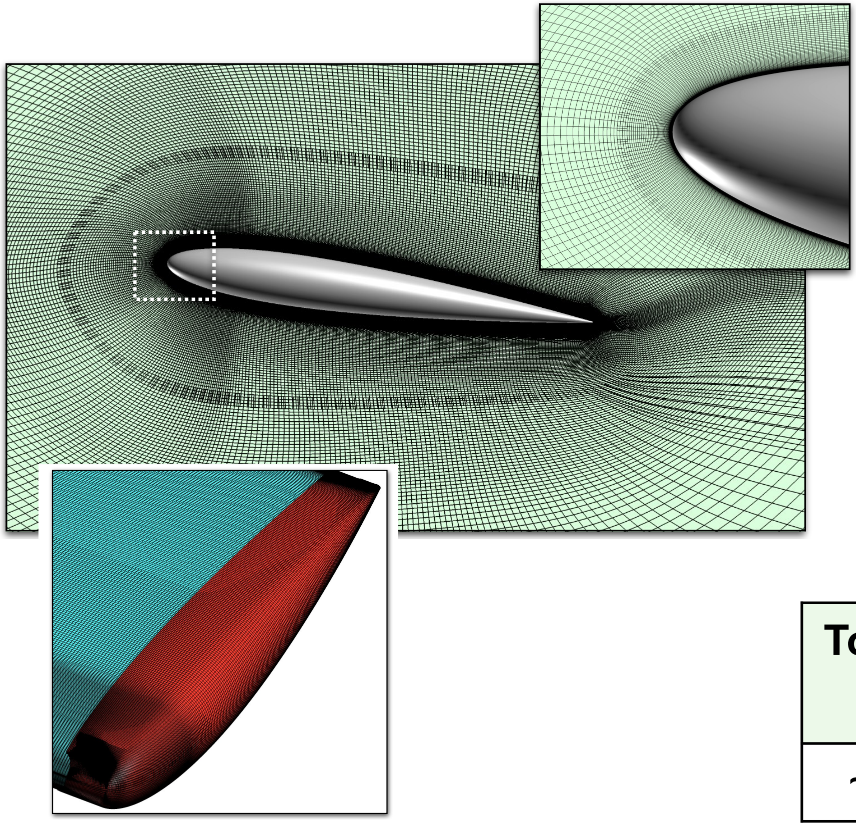
Shock/Boundary Layer Interaction in Front of Canonical Shapes

- Wall-mounted circular half-step
- Wall-mounted two-dimensional cylinder
- Wall-mounted hemisphere

Wing-Vortex Aerodynamics

Garmann and Visbal

- **Characterize the unsteady nature of a tip vortex generated on a wing subjected to high-frequency, low-amplitude oscillations (AIAA 2016-0328)**
- **Elucidate implications of wing/vortex motion in unsteady wake encounters or when in formation flight (AIAA 2015-1066, AIAA 2015-3073)**



Tip Vortex Study

Total cell count	Maximum Surface Spacing		
	$(\Delta n/c)_{max}$	$(\Delta s/c)_{max}$	$(\Delta z/c)_{max}$
~ 404M	0.005%	0.25%	0.20%

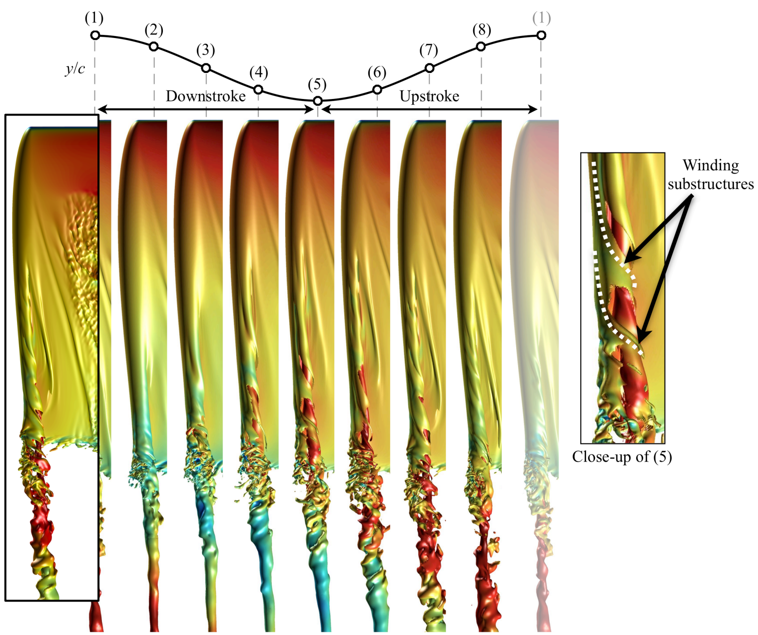
Wing-Vortex Interaction Study

Total cell count	Maximum Surface Spacing (×10^3)		
	Normal	Streamwise	Spanwise
~336M	0.052	5.093	5.000

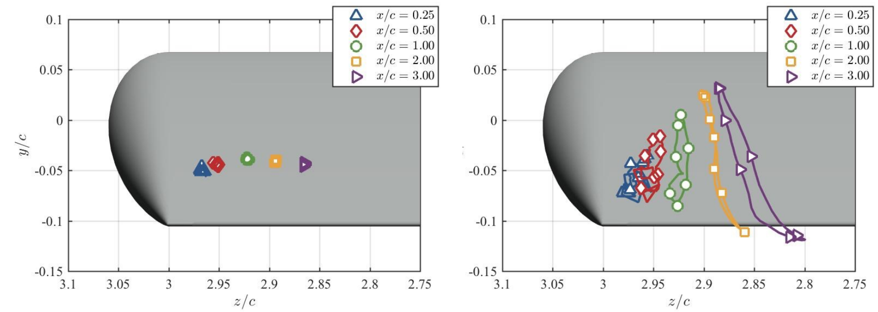
Wingtip Vortex Evolution

Garmann and Visbal

Surface Evolution



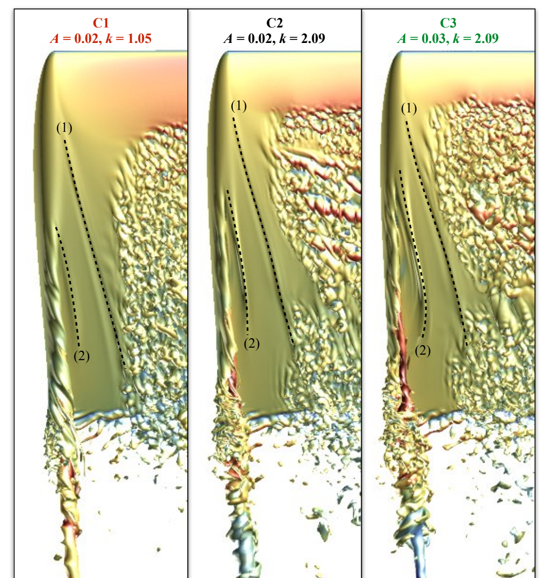
Induced orbital motion of tip vortex



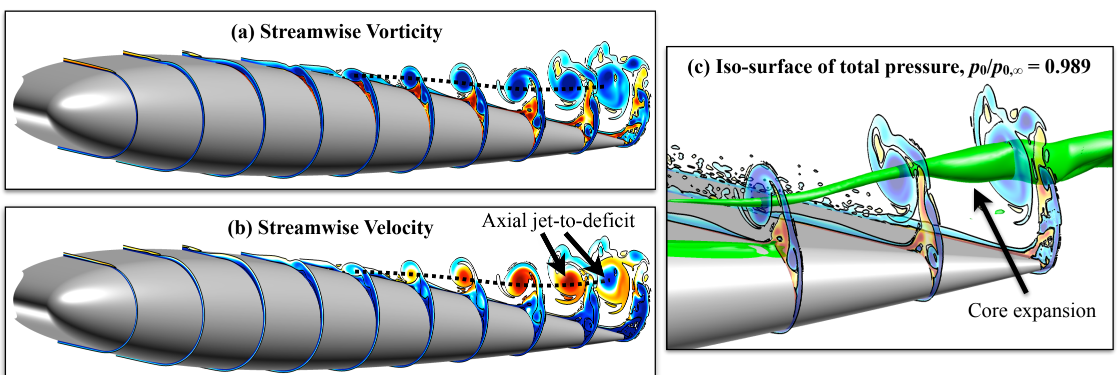
(a) Stationary wing

(b) Heaving wing

Effect of heaving frequency/amplitude



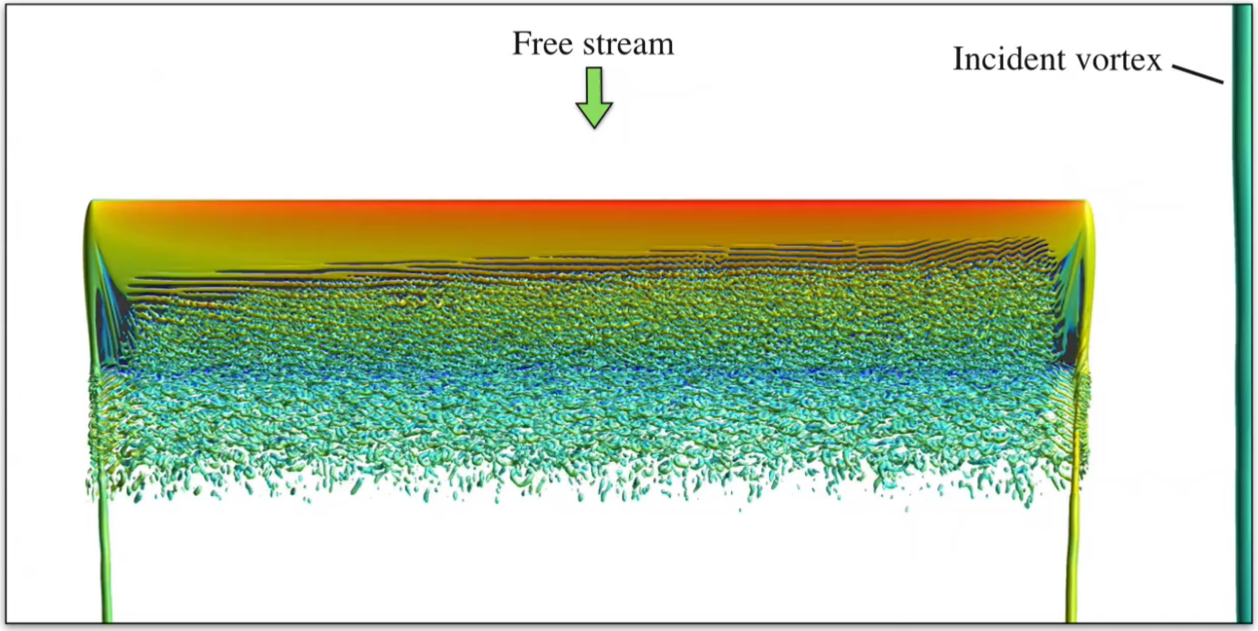
Transitory jet-to-wake/wake-to-jet events



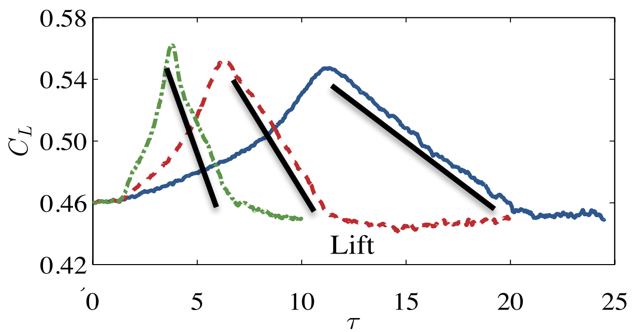
Wing/Streamwise Vortex Interaction

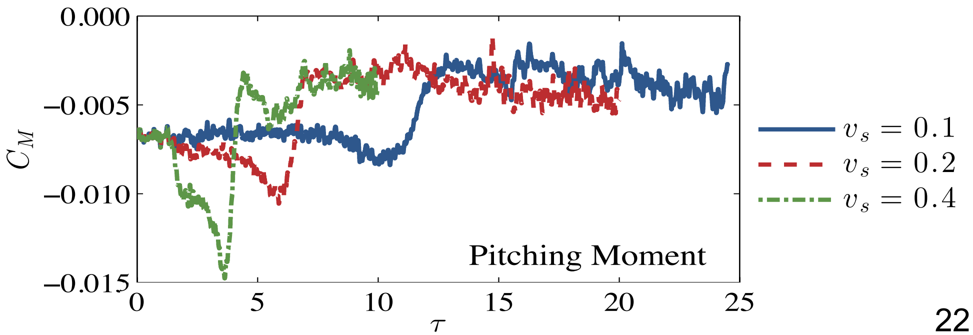
Garmann and Visbal

Three-dimensional flow structure for v_s = 0.1



Temporal variation of unsteady loads



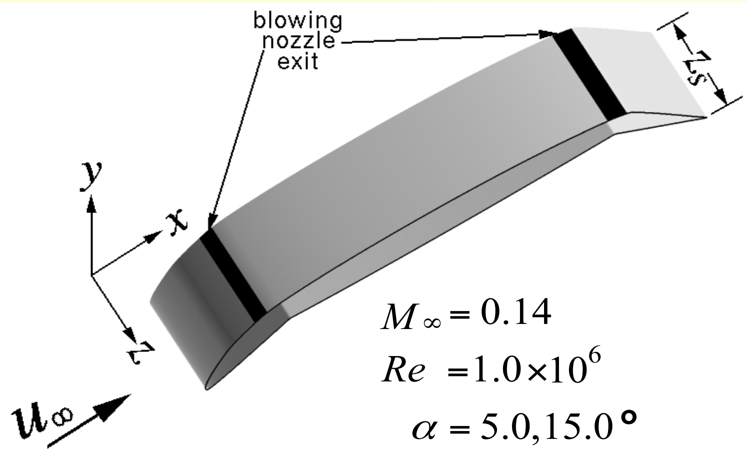


Flow Control for Laminar Airfoils

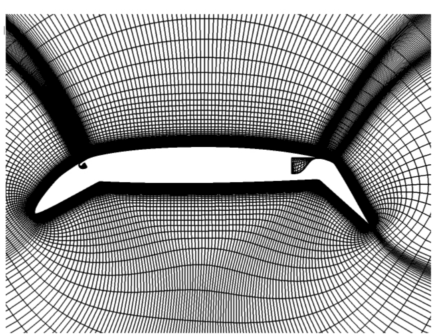
Rizzetta et al.

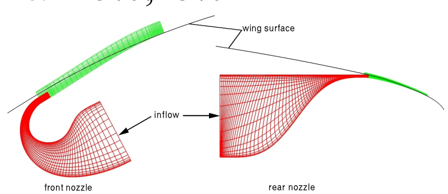
- Examine flow control concepts for Multi-Objective Leading-Edge Concept airfoil (MOLEC), a NASA design with a seamless, morphing leading-edge flap and a simple hinged trailing-edge flap (AIAA 2016-0322)

- Examine plasma control for delaying excrescence-generated transition due to spanwise-uniform or distributed roughness elements (AIAA 2015-3035)

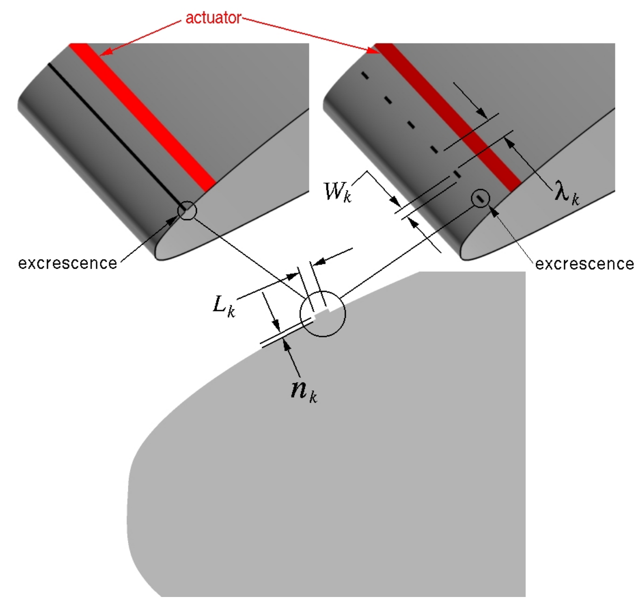


$$M_\infty = 0.14$$
$$Re = 1.0\times10^6$$
$$\alpha = 5.0, 15.0°$$





Fine grids
baseline - 186M
full-span nozzles - 223M
segmented nozzles - 321M

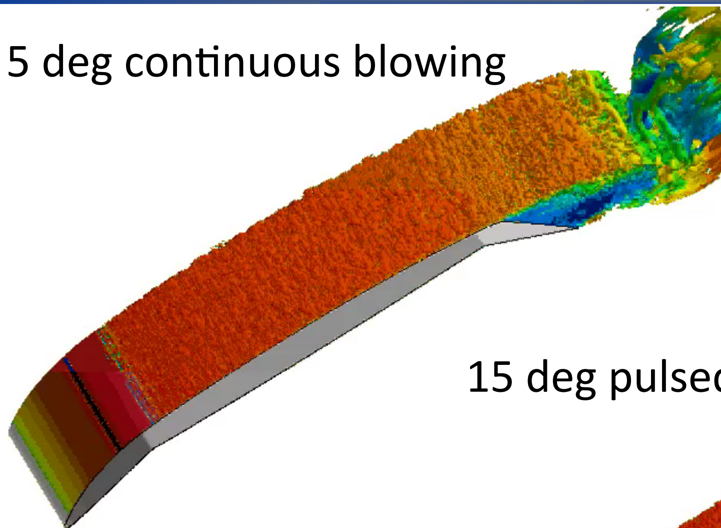


Fine grid – 134M pts

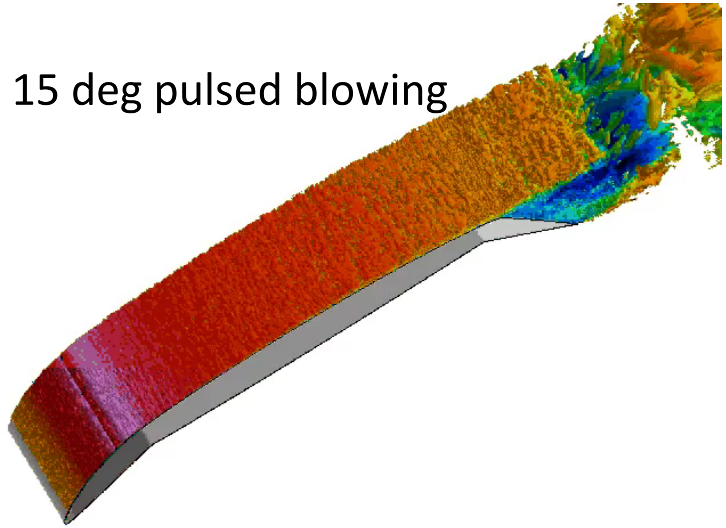
MOLEC AIRFOIL

RIZZETTA ET AL.

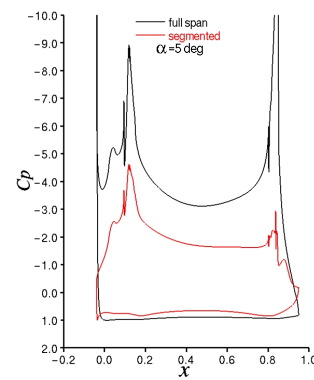
5 deg continuous blowing



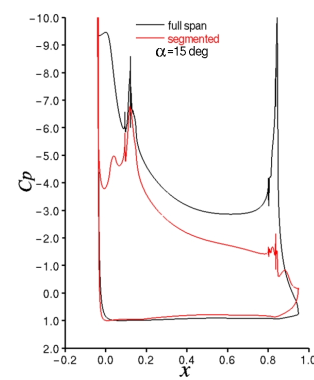
15 deg pulsed blowing



Full span vs. segmented blowing



= 5.0 deg



= 15.0 deg

configuration	α	Cl	$\overline{\dot{m}}$
continuous blowing	5	4.83	0.087
pulsed blowing	5	4.67	0.059
continuous blowing	15	4.98	0.087
pulsed blowing	15	4.23	0.059

3% < lift

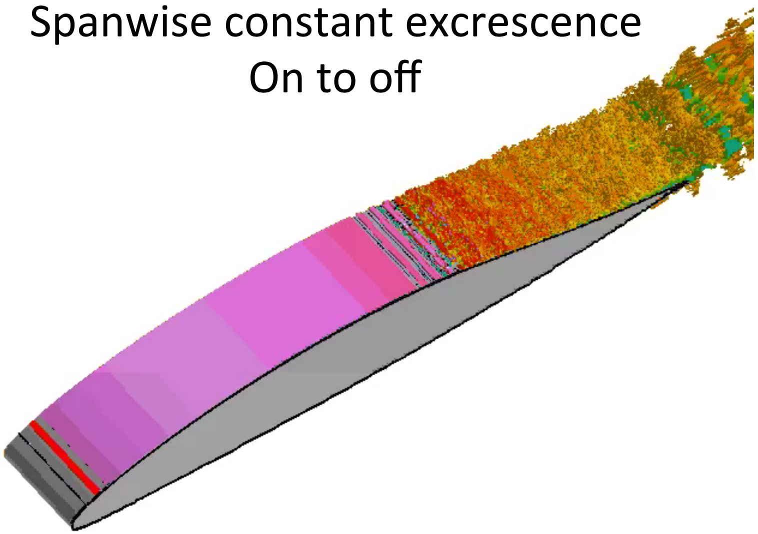
15% < lift

32% < mass flow

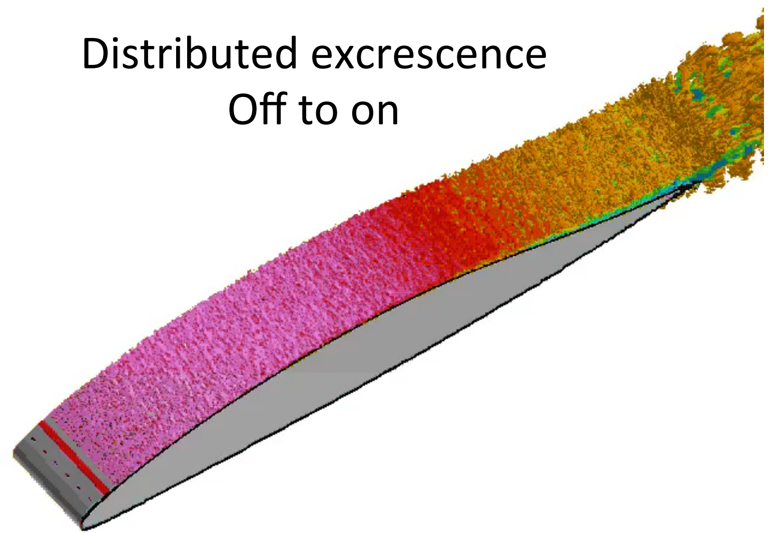
Plasma control with Excrescence

Rizzetta et al.

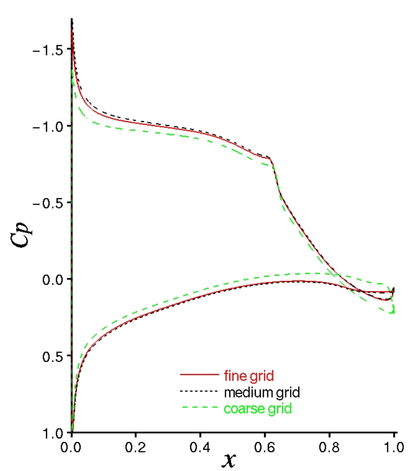
Spanwise constant excrescence
On to off



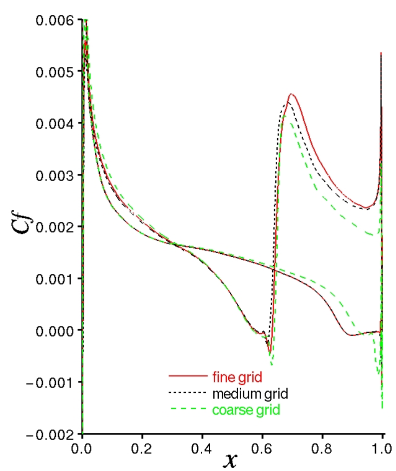
Distributed excrescence
Off to on



Grid convergence on no control case

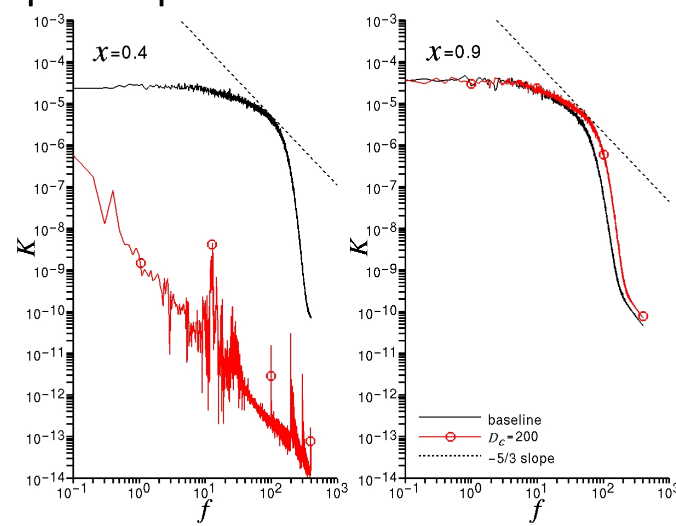


surface pressure



skin friction

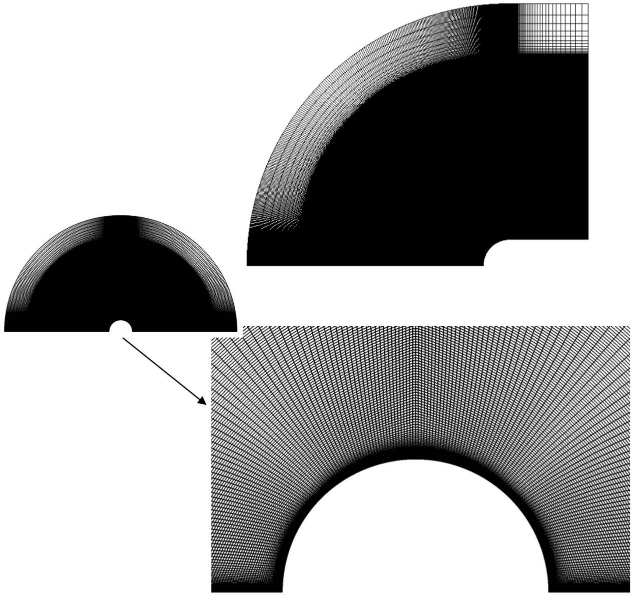
Temporal spectra at streamwise locations



SWBLI of Canonical Shapes

Morgan et al.

- Understand physics of unsteady SWBLI in front of wall-mounted shapes (step:AIAA 2015-2640,half-cylinder:AIAA 2016-0046,hemi:AIAA 2016-3650)
- Determine if DDES and hybrid RANS/LES models properly model SWBLI
- Investigate effects of grid topology and eventually compare to AMR results

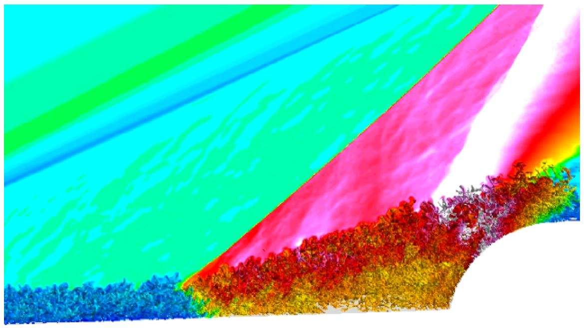


- Build up approach: step, cylinder, hemi
- Single-grid topology with various refinements (77.6M for half-step, 328M for fine cylinder, 300M for coarse hemi)
- Boundary layer tripped using plasma trip with Shyy body force model and allowed to transition naturally downstream
- Flow conditions -> M_∞=2.0, Re_R = 200K (step) / 300K (cyl/hemi)

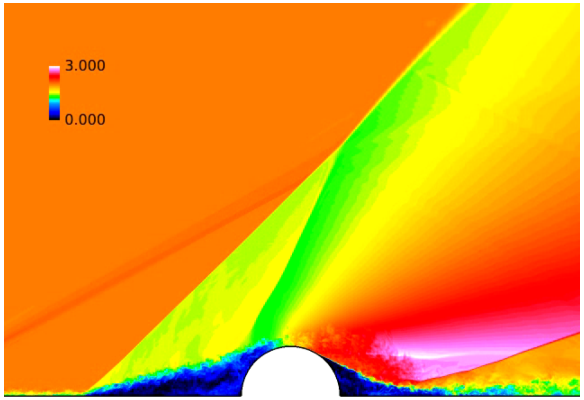
SWBLI of Canonical Shapes

Morgan et al.

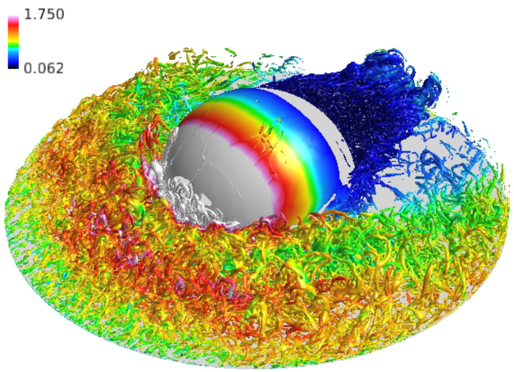
Half-step



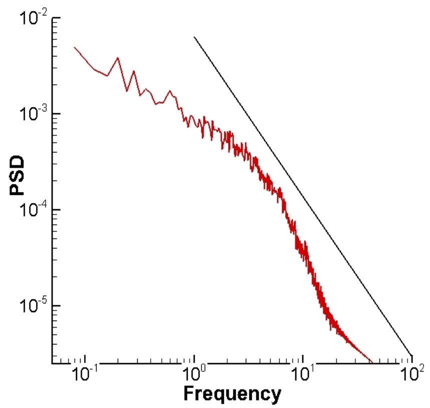
Cylinder



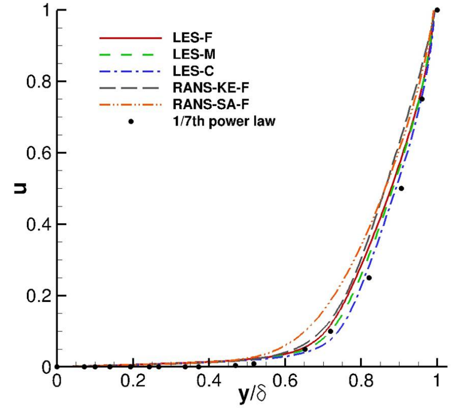
Hemisphere



PSD in sep bubble



Incoming TBL profile comparisons



Separation point comparison

Case	Upstream separation	Upstream reattachment
RANS-SA-F	-2.36	25.3^o
RANS-SA-M	-2.38	26.7^o
RANS-SA-C	-2.35	23.3^o
DDES-F	-2.74	21.6^o
DDES-M	-2.58	21.6^o
DDES-C	-2.40	23.3^o
LES	-2.22	25.4^o

Summary and Conclusions

- FDL3DI is a powerful, high-order, structured overset CFD solver developed in AFRL/RQV
  - Scalable and efficient
  - Implicit LES capability
  - Compact scheme with filtering, hybrid shock capturing, high-order interpolation, hole handling
- Used to discover fundamental physics associated with complex, multi-disciplinary fluid dynamic problems
- Used in combination with OVERFLOW (much shared infrastructure) by my branch, and other unstructured solvers (FUN3D, AVUS) within the Comp Sci Center
- Recent upgrades (BUNGe and FDLv2) have significantly improved usability and functionality