Verification of Unstructured Grid Adaptation Components

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Motivation

Supporting Certification by Analysis

- Demands the accurate simulation of steady and time-dependent separated flows for complex configurations
- Requires improved automation and robustness for complex geometry models and database creation
- Includes verification and validation exercises for the entire adaptive grid tool chain

Finding 3 of the CFD Vision 2030 Study[1]

Mesh generation and adaptivity continue to be significant bottlenecks in the CFD [Computational Fluid Dynamics] workflow, and very little government investment has been targeted in these areas.

[1] Slotnick et al. CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences NASA CR-2014-218178

Inspiration

Turbulence Modeling Resource (TMR)

Resource for CFD developers to:

- Obtain accurate and up-to-date turbulence models, and
- Verify model implementation.

Public website `https://turbmodels.larc.nasa.gov` provides:

- References, equations, and clarifications for each model
- Fixed grids and CFD results for verification (of model implementation)
- Experimental measurements for validation (of model to reality)

Goal: create an equivalent data set for unstructured grid adaptation

Unstructured Grid Adaptation Working Group

Public website `https://UGAWG.GitHub.io`

- Verification benchmark test cases
- Encourage detailed implementation discussion between researchers
- Encourage new entrants into adaptive grid research

AIAA Paper 2015-2292

2D and 3D output-based and analytic-metric adaptation

AIAA Paper 2016-3323

Recommendations for CFD Vision 2030 investment and potential impacts

International Meshing Roundtable 2017

First benchmark of the Unstructured Grid Adaptation Working Group

AIAA Paper 2018-1103

Test cases and results included in benchmark repository and website

Today

AIAA Paper 2019-1995 Kingston Peak, 3:30pm

Parallel Anisotropic Unstructured Grid Adaptation

- Strong and weak grid adaptation scaling studies to specified metrics
- Equivalent metric conformity independent of core count (not identical to sequential execution)

Today's Talk: AIAA SciTech 2019

Verification of Unstructured Grid Adaptation Component

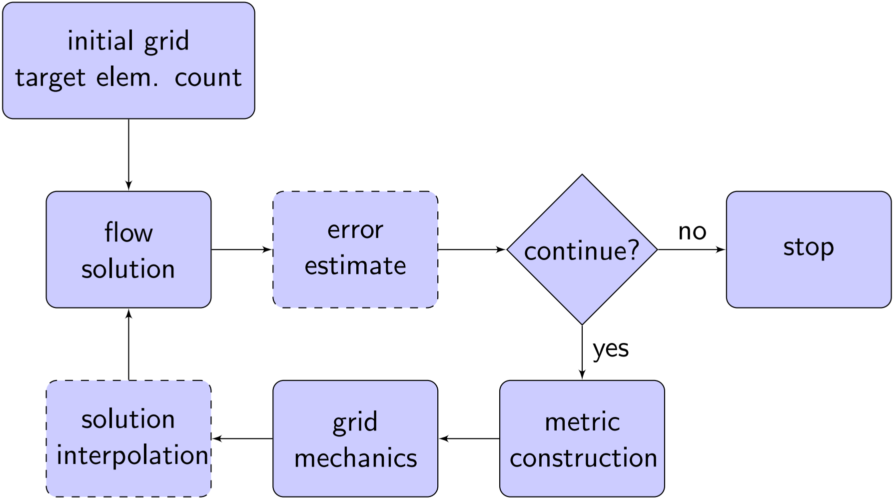
- Interchange individual components of the grid adaptation process
- Design-order grid adaptation to analytic fields:
  - scalar L^2-approximations
  - scalar advection-diffusion PDE
- Code-to-code comparison:
  - laminar delta wing
  - turbulent ONERA M6

Outline

1. Grid Adaptation Components
2. Verification with Scalar Fields
3. Integrated Grid Adaptation Processes: Laminar Delta Wing
4. Integrated Grid Adaptation Processes: ONERA M6
5. Conclusions and Future Work

Outline

Integrated Grid Adaptation Process

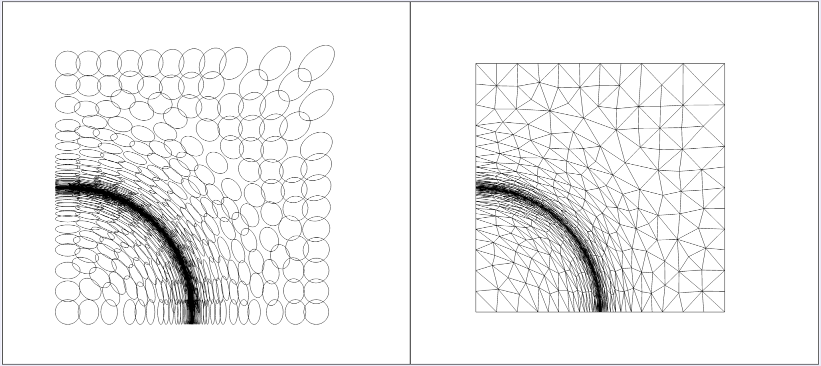


Metric-Based Unstructured Grid Adaptation

Metric Field

- Describes a request of grid density, stretching, and orientation
- Constructed to control interpolation or output error

Metric Field Rendered as Ellipses and Unit Grid



Flow Solvers

GGNS - Boeing Company

- Streamline Upwind Petrov-Galerkin (SUPG) finite-element method

Wolf - INRIA

- Unstructured MUSCL (UMUSCL) finite-volume method

FUN3D - NASA

- FUN3D-FV: Upwind finite-volume method
- FUN3D-SFE: Stabilized continuous finite-element method

Firedrake - Imperial College London

- Streamline Upwind Petrov-Galerkin (SUPG) finite-element method

SANS - Massachusetts Institute of Technology

- Continuous and Discontinuous finite-element method
- Dual Weighted Residual (DWR) error estimate

Metric Construction Methods

Multiscale

- L^2-projection Hessian reconstruction (Mach number)
  - Wolf
    - Boundary Hessian extrapolated from interior
  - refine
    - Boundary Hessian extrapolated from interior
  - Firedrake
    - No boundary Hessian treatment
- *k*-exact Hessian reconstruction (Mach number)
  - GGNS
  - refine

MOESS - Mesh Optimization via Error Sampling and Synthesis

- Optimal step matrix to minimize error estimate
  - SANS
- Works with High-Order methods

Grid Adaptive Mechanics Methods

EPIC - Boeing Company

- EPIC-ICS: insertion, collapse, and swap
- EPIC-ICSM: insertion, collapse, swap, and node movement

FEFLO.A - INRIA

- Cavity-based operator

refine - NASA

- Insertion, collapse, and node movement

PRAgMaTic - Imperial College London

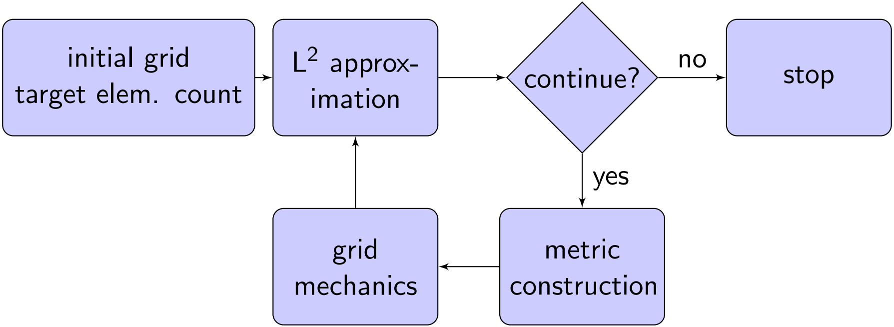
- Insertion, collapse, swap, and node movement

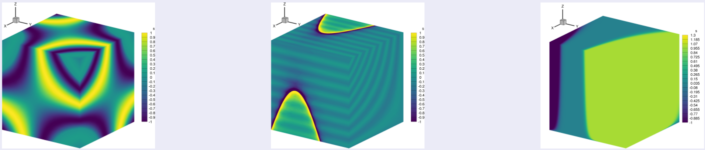
avro - Massachusetts Institute of Technology

- Cavity-based operator

Outline

Integrated Grid Adaptation Process: Scalar Field





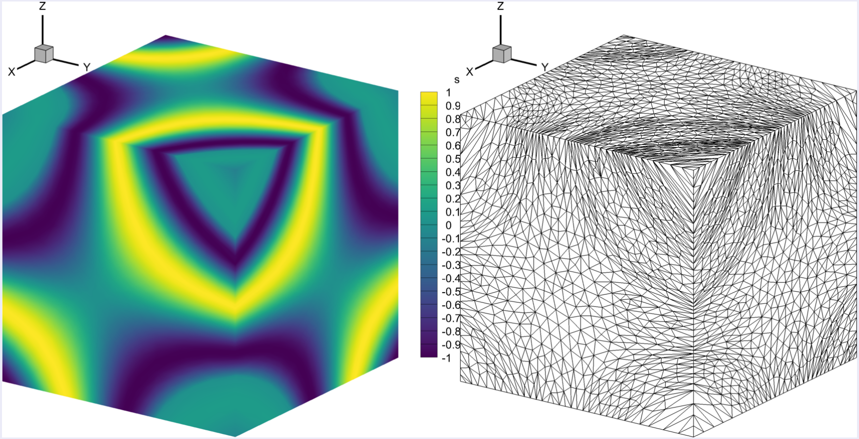
L^2-error converge with rate p+1 with increaesed target element count

Grid Adaptation Components: Scalar Field

L^2 approx.	metric construction	grid mechanics
• SANS-DG • SANS-CG	• refine - L^2-project • refine - k-exact • SANS - MOESS	• EPIC • refine • FEFLO.A • avro
Firedrake	• refine - L^2-project • refine - k-exact • Firedrake - L^2-proj.	• PRAgMaTic

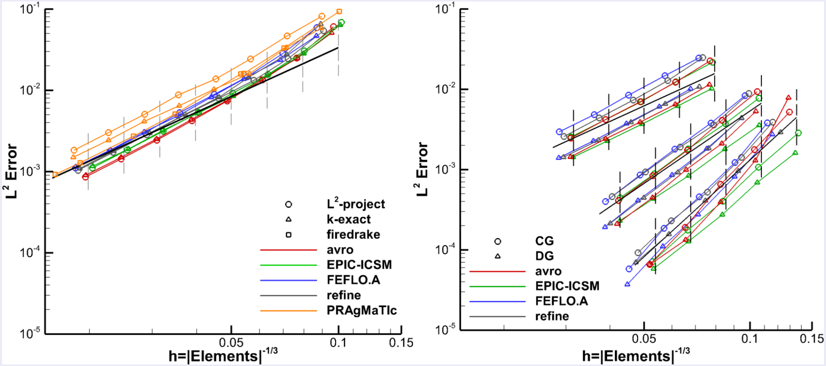
sinfun3 Scalar Function and 128,000 Element Grid

Smooth and Weakly Anisotropic



sinfun3 Interpolation Error Convergence

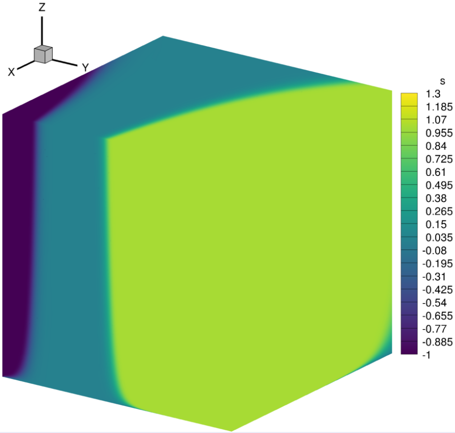
Multiscale and MOESS

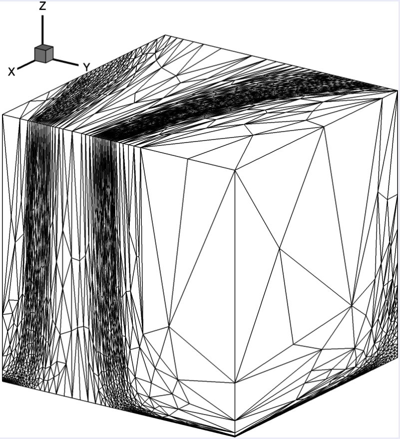


Consistent $p+1$ convergence (black lines) for all methods

tanh3 Scalar Function and 128,000 Element Grid

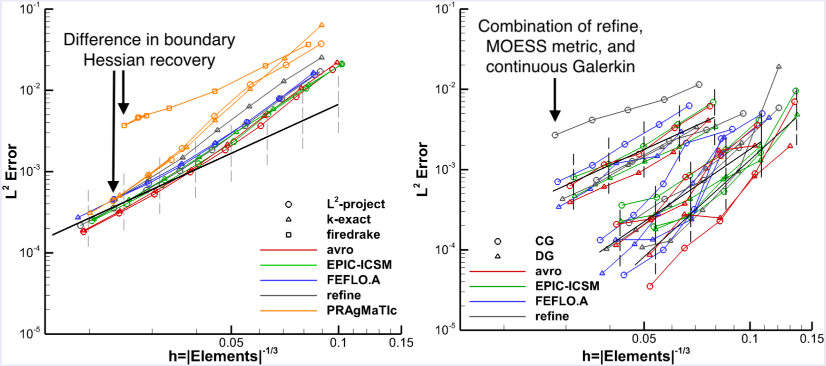
Curved Anisotropic Boundary and Shear Layers





tanh3 Interpolation Error Convergence

Multiscale and MOESS



Consistent $p+1$ convergence for most, some have higher error levels

Verification of Scalar Fields

Summary

- Majority of methods show expected convergence rate for sufficiently smooth problems
- Code-to-code comparisons to aid in identifying method deficiencies

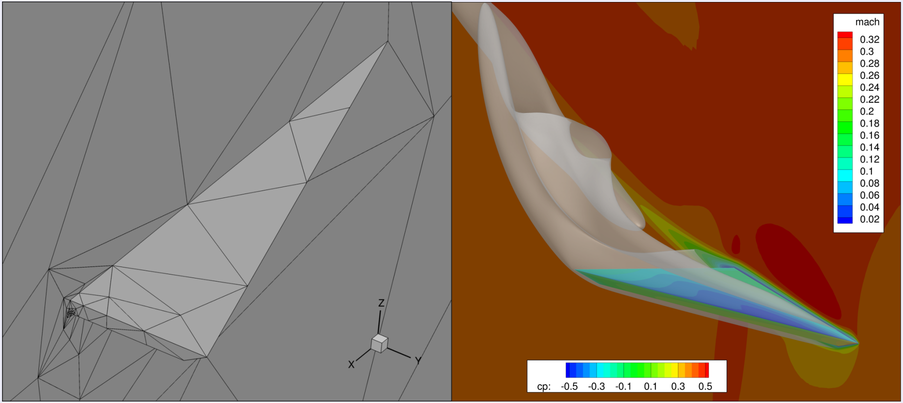
In Paper

- `sinatan3` field with curved shock feature and low amplitude background variation
- `TripleBL` scalar convection diffusion boundary layer model with corners
- Detailed appendix with complete set of results for each method

Outline

Laminar Delta Wing

Coarse Initial Grid without Boundary Layer Refinement



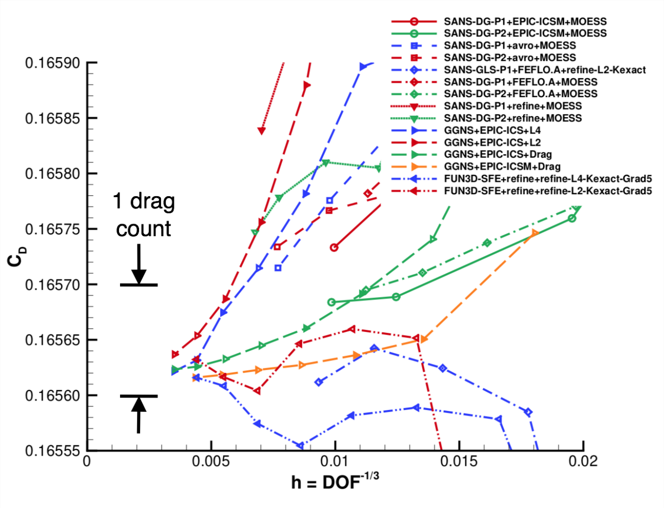
Test case with a strong leading edge vortex used in the first three International Workshops on High Order CFD Methods

Laminar Delta: Grid Adaptation Components

flow/adjoint solution	metric construction	grid mechanics
SANS	• refine - *k*-exact • SANS - MOESS	• EPIC • refine • FEFLO.A • avro
GGNS	• GGNS - *k*-exact	• EPIC
FUN3D-SFE	• refine - *k*-exact	• refine

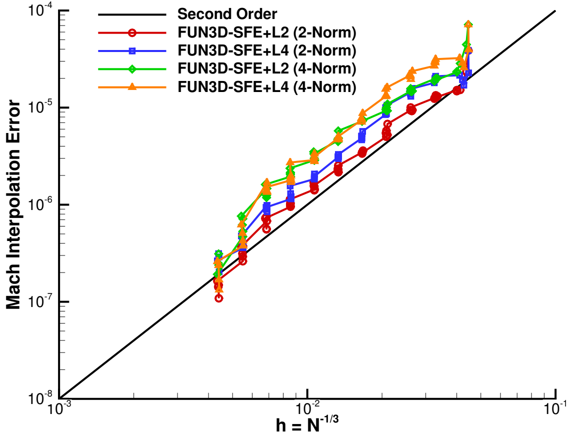
Laminar Delta: 0.3 Mach, 4K Re_{Root}, 12.5° AoA

Drag coefficient



Laminar Delta: 0.3 Mach, 4K Re_{Root}, 12.5° AoA

Mach Interpolation Error



Laminar Delta: Summary

Summary

- For grids above 10M vertices
  - less than a half a drag count variation
  - less than 0.06% variation in lift coefficient
- Modeling Difference in SANS vs. FUN3D-SFE vs. GGNS?
  - SANS+EPIC p=2 converged with 512k DOF according to error estimate

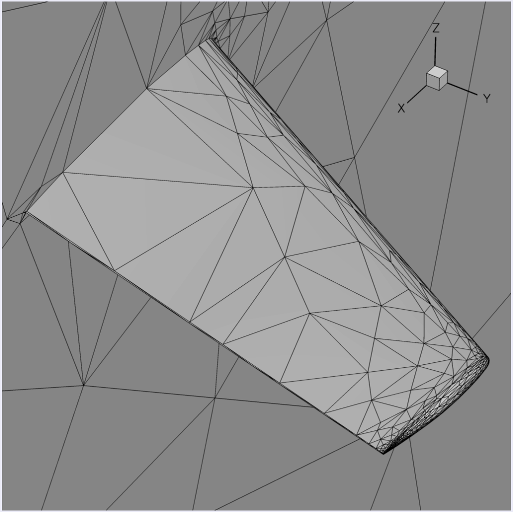
In Paper

- Lift Coefficient

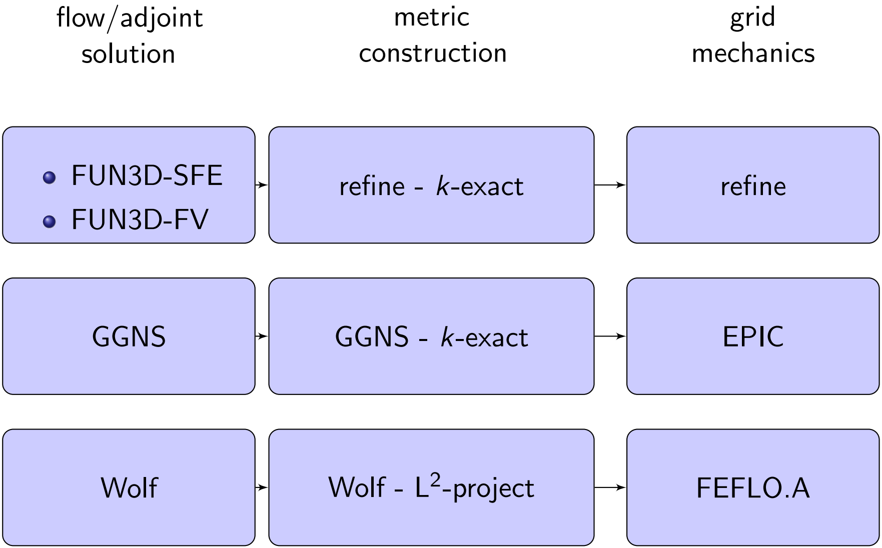
Outline

ONERA M6 Wing

Curvature resolving initial grid without boundary layer refinement

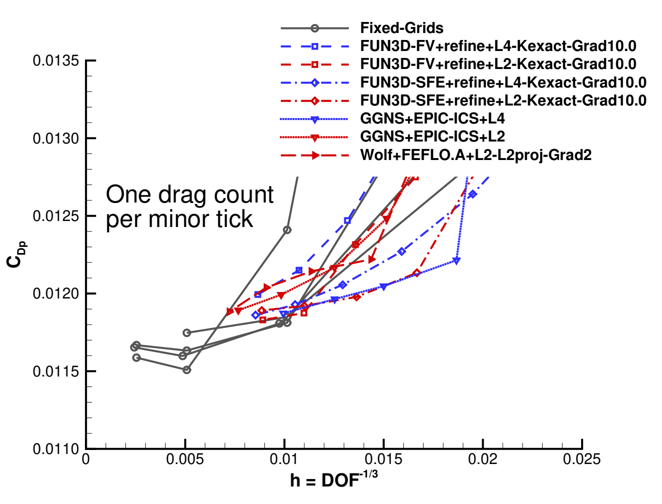


ONERA M6: Grid Adaptation Components



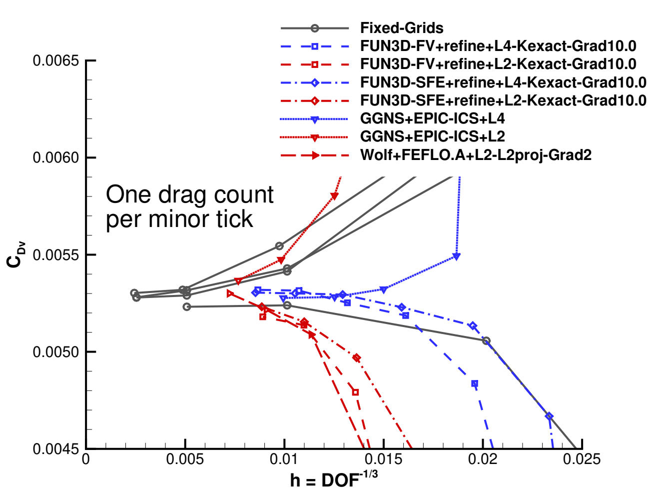
ONERA M6: 0.84 Mach, 14.6M Re_{Root}, 3.06° AoA

Pressure Component of Drag Coefficient



ONERA M6: 0.84 Mach, 14.6M Re_{Root}, 3.06° AoA

Viscous Component of Drag Coefficient



ONERA M6: Summary

Summary

- Pressure and viscous drag coefficient components approach fine fixed-grid values
- Less than a two count drag count variation for adapted grids

In Paper

- GGNS+EPIC-ICSM output-adapted
- Wolf+FEFLO.A output-adapted
- Detailed appendix with complete set of results for each method

Conclusions

Verification of Grid Adaptation

- Design order (second and higher) demonstrated for sufficiently regular functions
- New adaptive grid mechanics implementation (avro)
- Detailed appendix in the paper to form the expected behavior of adaptive grid tools

Integrated Grid Adaptation Processes

- Unstructured to the wall, valid, and boundary conforming to geometry
- Improvements to all integrated grid adaptation implementations demonstrated since SciTech 2018

Outreach and Acknowledgment

Unstructured Grid Adaptation Working Group (UGAWG)

- Informal group with monthly virtual meetings
- `https://UGAWG.GitHub.io`
- Grids and test cases available for analysis or developing new methods
- `UGAWG@Mail.EmailHorse.com` or `Mike.Park@NASA.gov`

Acknowledgment

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