Verification of Unstructured Grid Adaptation Components

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Motivation

Supporting Certification by Analysis

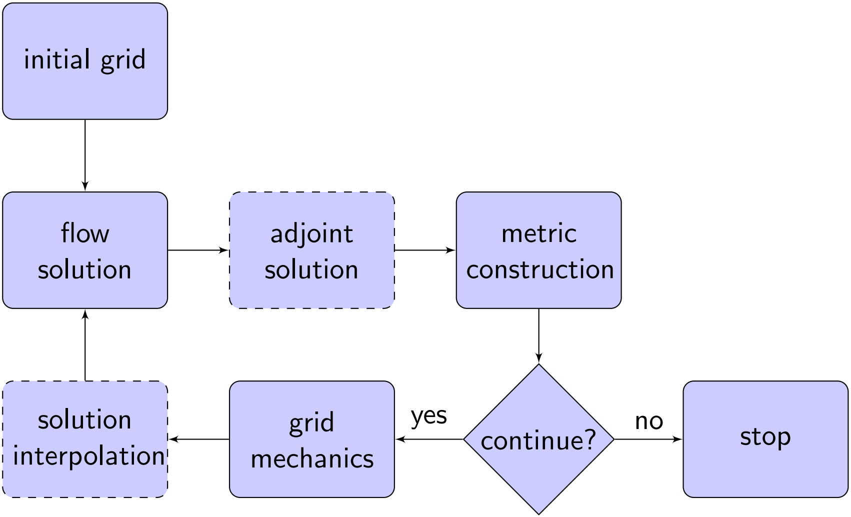
- Demands the accurate simulation of steady and time-dependent separated flows for complex configurations
- Requires improved automation and robustness for complex geometry models and database creation
- Includes verification and validation exercises for the entire adaptive grid tool chain

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

Integrated Grid Adaptation Process



Motivation

Methodology

- Evaluate integrated grid adaptation process performance on
  - Analytic functions
  - Scalar partial differential equations with an analytic solution
  - Code-to-code comparison on laminar and turbulent test cases
- Interchange individual components of the grid adaptation process
- Define expected performance in terms of interpolation error convergence and/or output convergence
- Encourage detailed implementation discussion between researchers
- Encourage new entrants into adaptive grid research

Inspiration

Turbulence Modeling Resource (TMR)

The objective is to provide a resource for CFD developers to:

- Obtain accurate and up-to-date information on widely-used turbulence models, and
- Verify that models are implemented correctly.

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

Related Work

AIAA Paper 2015-2292

Comparing Anisotropic Output-Based Grid Adaptation Methods by Decomposition

- 2D and 3D output-based and analytic-metric adaptation for planar geometries
- Descriptive statistics and output convergence to quantify performance

AIAA Paper 2016-3323

Unstructured Grid Adaptation: Status, Potential Impacts, and Recommended Investments Toward CFD Vision 2030

- Literature survey
- Unstructured grid adaptation status and 15 year forecast
- Recommendations for investment and potential impacts

Related Work

International Meshing Roundtable 2017

First benchmark of the Unstructured Grid Adaptation Working Group

- 3D analytic-metric adaptation for a planar geometry and simple curved surface geometry model
- Creation of a benchmark repository and website

AIAA Paper 2018-1103

Unstructured Grid Adaptation and Solver Technology for Turbulent Flows

- Descriptive statistics of adapted grid metric conformity
- 3D interpolation error and output-based metrics for Hemisphere Cylinder and ONERA M6
- Test cases and results included in benchmark repository and website

Related Work

AIAA SciTech 2019

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

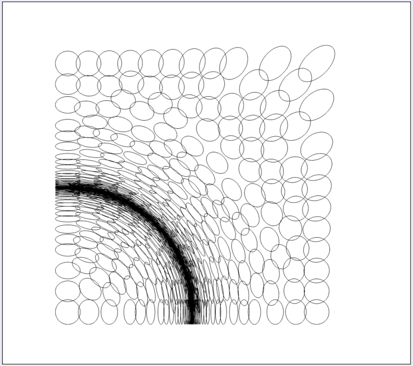
- Design-order grid adaptation to analytic fields
- Code-to-code comparison for laminar delta wing and turbulent ONERA M6

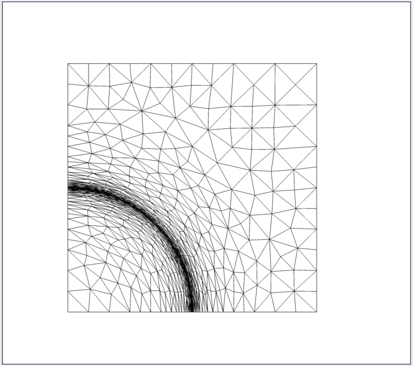
Metric-Based Unstructured Grid Adaptation

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

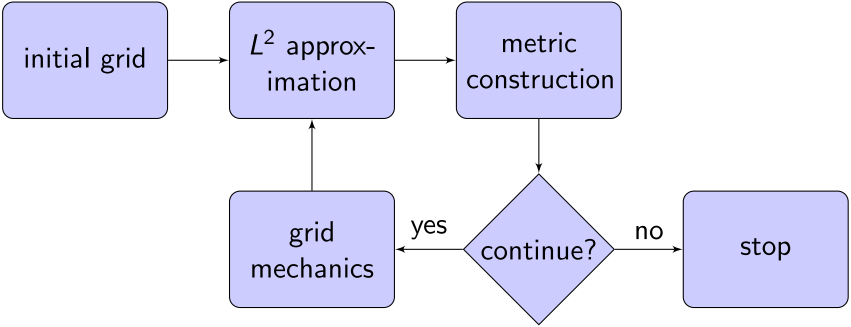




Outline

1. Motivation and Introduction
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

Integrated Grid Adaptation Process: Scalar Field



Grid Adaptive Mechanics Methods

EPIC

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

refine

- NASA
- Insertion, collapse, and node movement

FEFLO.A

- INRIA
- Cavity-based operator

Grid Adaptive Mechanics Methods

avro

- Massachusetts Institute of Technology
- Cavity-based operator

PRAgMaTic

- Imperial College London
- Insertion, collapse, swap, and node movement

Metric Construction Methods

L^2-project

- Multiscale with L^2-projection Hessian reconstruction implemented in refine
- Boundary Hessian extrapolated from interior

k-exact

- Multiscale with k-exact Hessian reconstruction implemented in refine

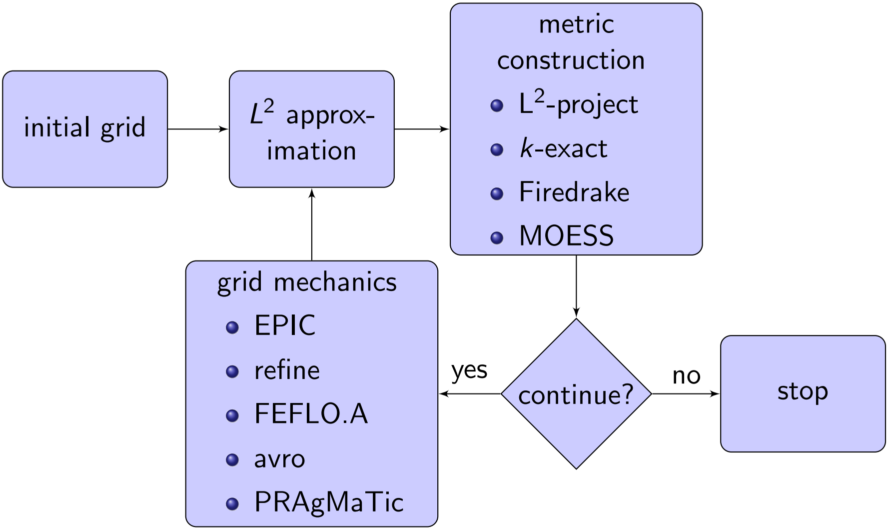
Firedrake

- Multiscale with L^2-projection Hessian reconstruction implemented in Firedrake

MOESS

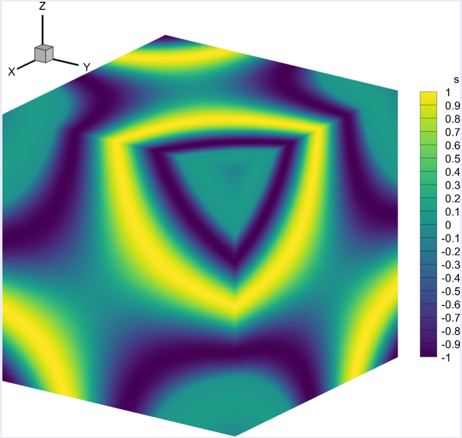
- Implemented in SANS
- Optimizes exact interpolation error

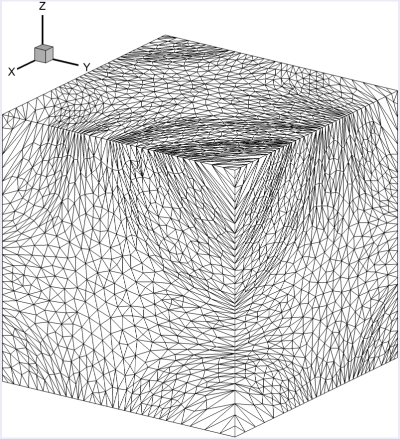
Integrated Grid Adaptation Process: Scalar Field



sinfun3 Scalar Function and 128,000 Element Grid

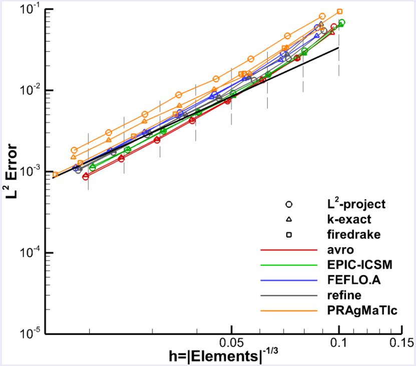
Smooth and Weakly Anisotropic

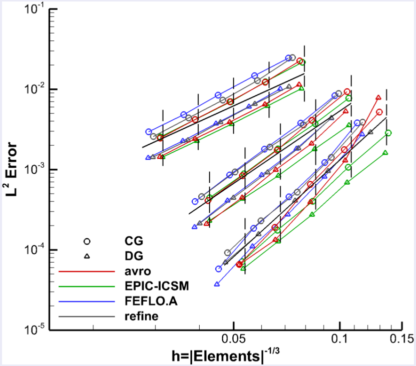




sinfun3 Interpolation Error Convergence

Multiscale and MOESS

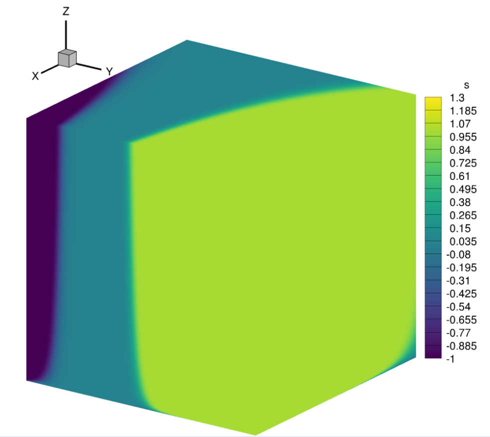


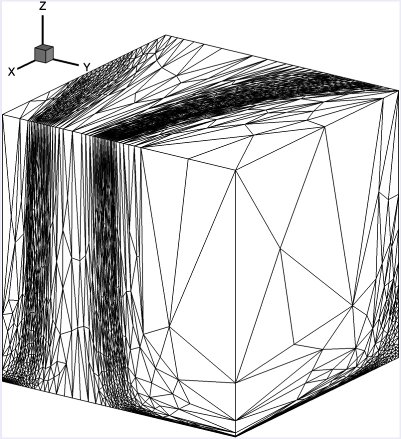


Consistent $p+1$ convergence (black lines) for all methods

tanh3 Scalar Function and 128,000 Element Grid

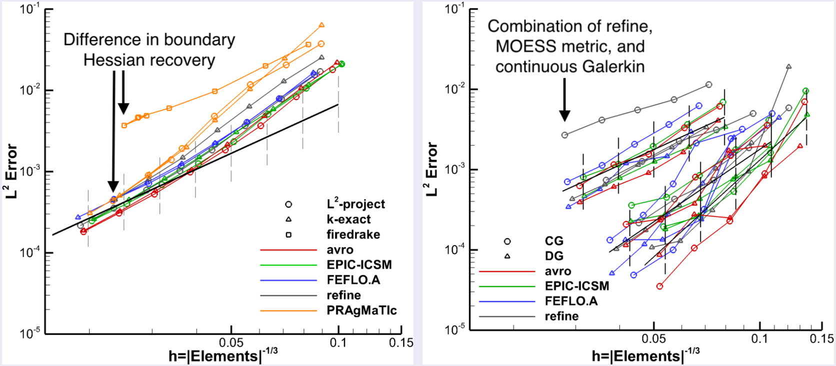
Curved Anisotropic Boundary and Shear Layers





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

- `tanh3` 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

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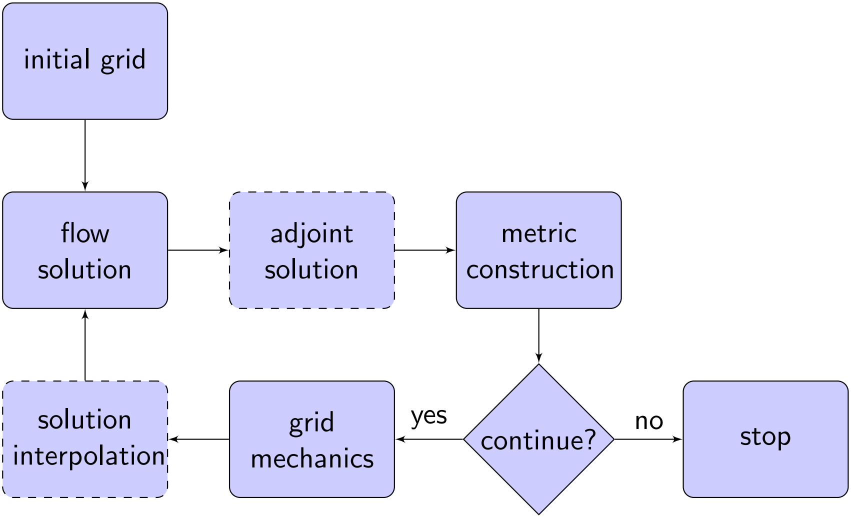
4 Integrated Grid Adaptation Processes: ONERA M6

5 Conclusions and Future Work

Integrated Grid Adaptation Process



Finite-Element Flow Solvers

SANS

- Massachusetts Institute of Technology
- Continuous and discontinuous finite-element method

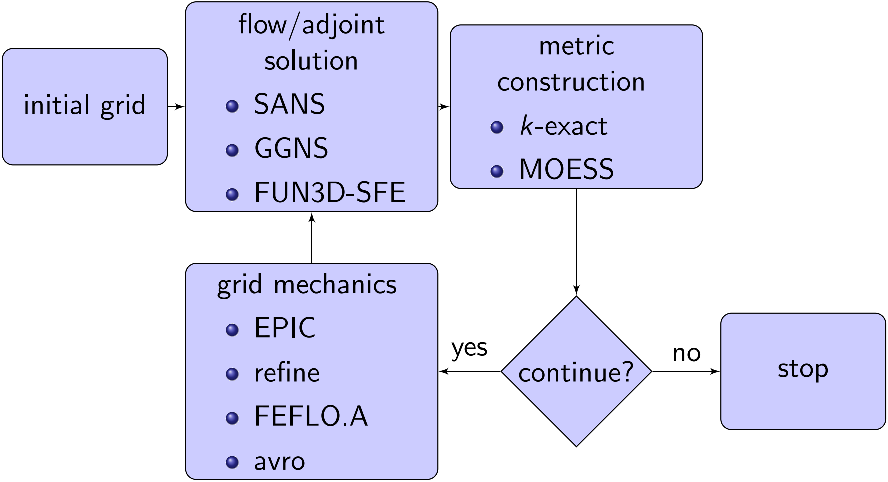
GGNS

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

FUN3D-SFE

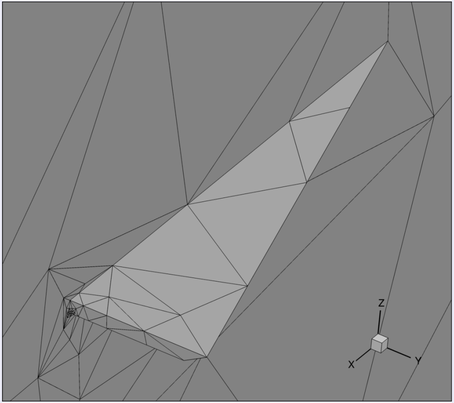
- NASA
- Stabilized continuous finite-element method

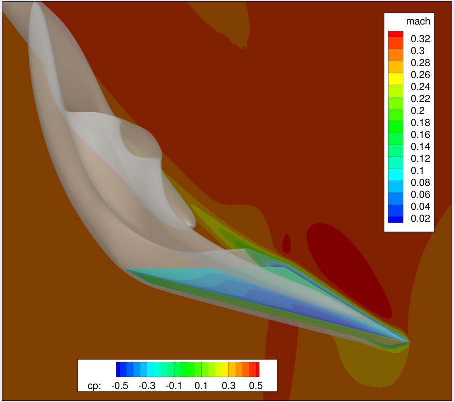
Integrated Grid Adaptation Process



Laminar Delta Wing

Coarse Initial Grid without Boundary Layer Refinement

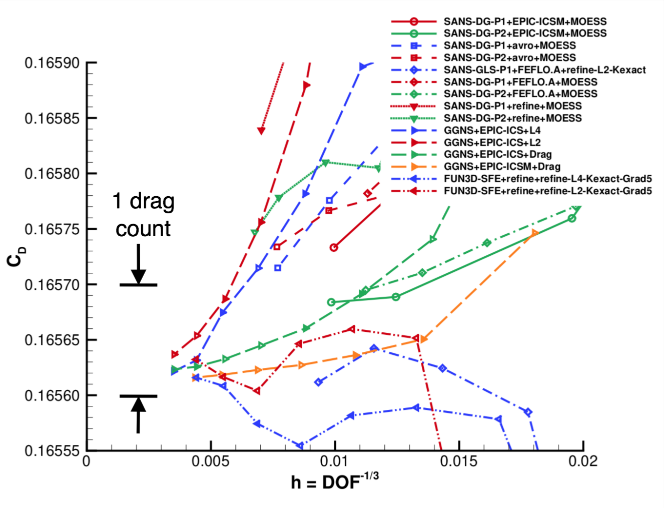




Test case with a strong leading edge vortex used in the first three International Workshops on High Order CFD Methods

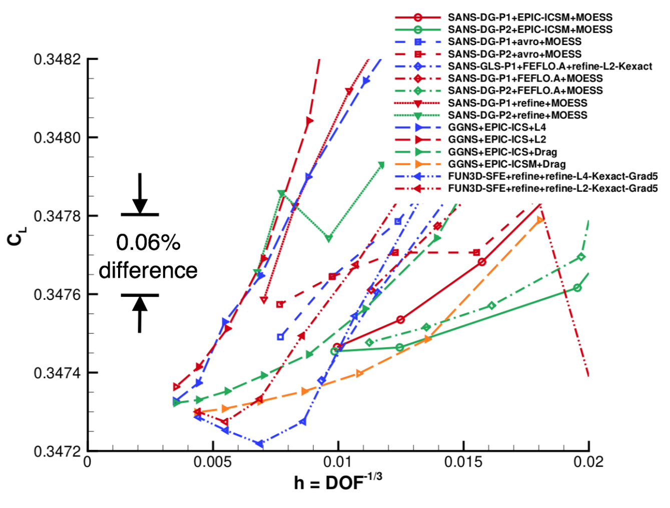
Laminar Delta, 0.3 Mach, 4K Re_{Root}, 12.5° AoA

Drag coefficient



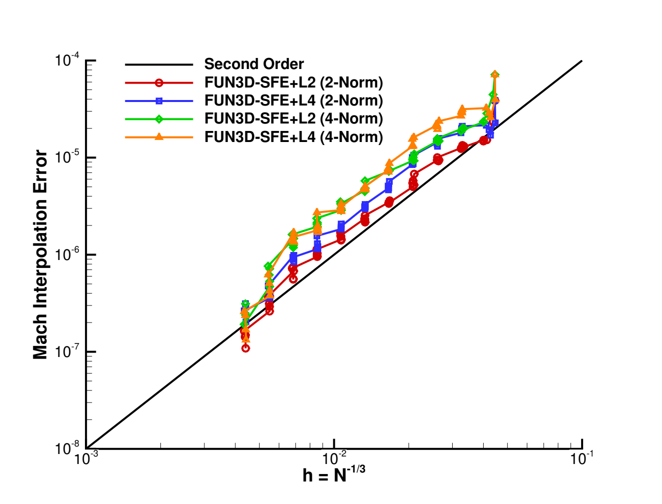
Laminar Delta, 0.3 Mach, 4K Re_{Root}, 12.5° AoA

Lift Coefficient



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

Mach Interpolation Error



Integrated Grid Adaptation Processes: Laminar Delta Wing

Summary

- For grids above 10M vertices
  - less than a half a drag count variation
  - less than 0.06% variation in lift coefficient

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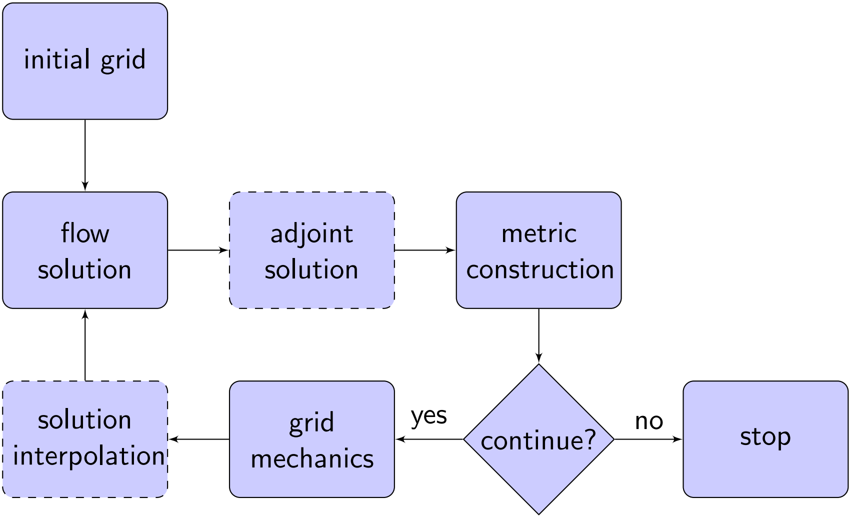
Integrated Grid Adaptation Process



Finite-Volume Flow Solvers

FUN3D-FV

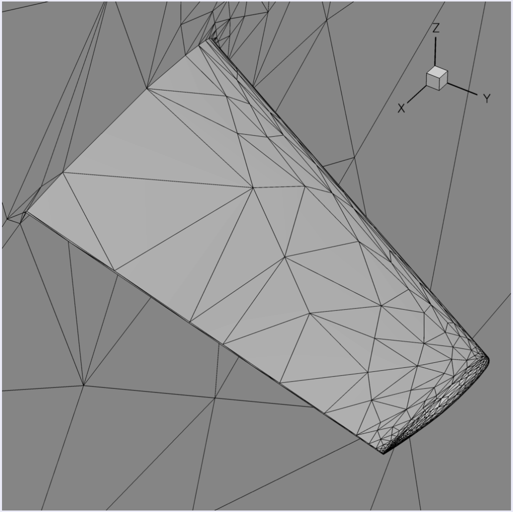
- NASA
- Upwind finite-volume method

Wolf

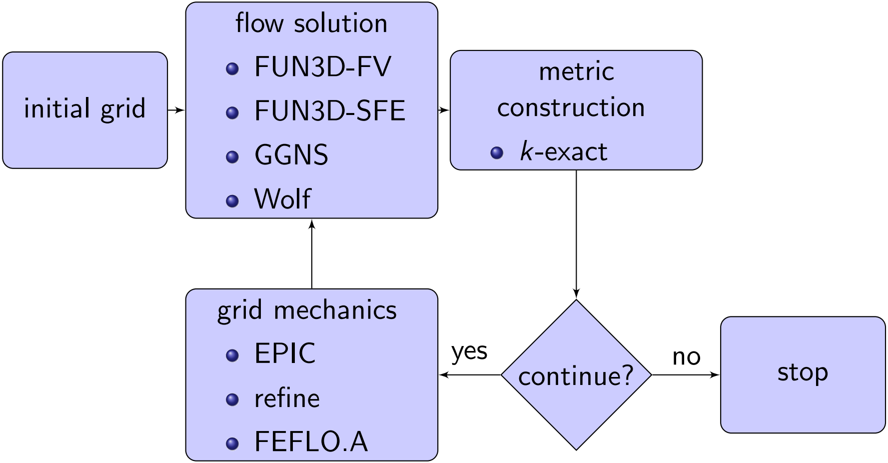
- INRIA
- Unstructured Monotonic Upwind Scheme for Conservation Laws (UMUSCL) finite-volume method

ONERA M6 Wing

Curvature resolving initial grid without boundary layer refinement

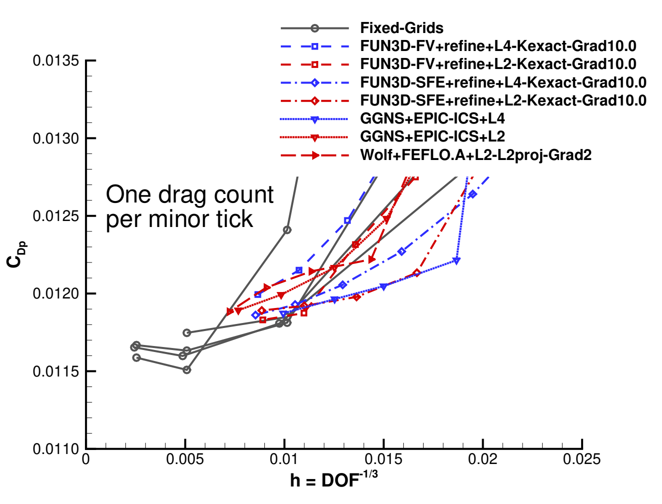


Verify Multiscale Metric Grid Adaptation Process



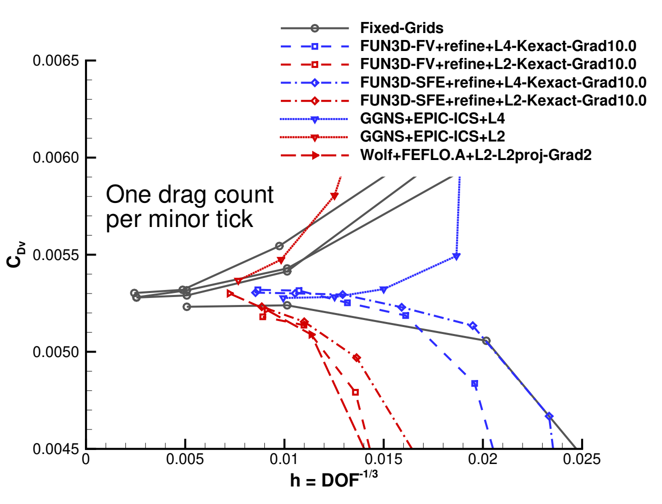
ONERA M6, 0.84 Mach, 14.6M Re_{Root}, 3.06° AoA

Pressure Component of Drag Coefficient



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

Viscous Component of Drag Coefficient



Integrated Grid Adaptation Processes: ONERA M6 Wing

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

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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

Future Work

Next Steps and Recommendations

- Investigate where combinations of metric construction methods and adaptive grid mechanics did not perform as well as their peers

Future Work (see also AIAA Paper 2016-3323)

Through Systemic Creation and Evaluation of Benchmark Cases

- Error estimation for turbulent flows (Reynolds-averaged or eddy-resolving)
- Accept issues present in typical complex geometry models
- Adaptive curved grids for higher-order schemes
- Efficiency on current and emerging high performance computing platforms

Adaptive Grid Computations Displace Fixed Grids as the Default

- Technology diffusion strategy for verified methods
- Demonstration on a wide range of industry-relevant configurations
- Partnership with commercial entities

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

This work was partially supported by the Transformational Tools and Technologies (TTT) Project of the NASA Transformative Aeronautics Concepts Program (TACP)