Unstructured Grid Adaptation and Solver Technology for Turbulent Flows AIAA Paper 2018-1103

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Motivation

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.

Methodology

- Encourage detailed implementation discussion between researchers
- Examine integrated grid adaptation processes and components
- Define expected performance, not “eye-ball norm” or “high quality”
- Encourage new entrants into adaptive grid research

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

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 content for a TMR of 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

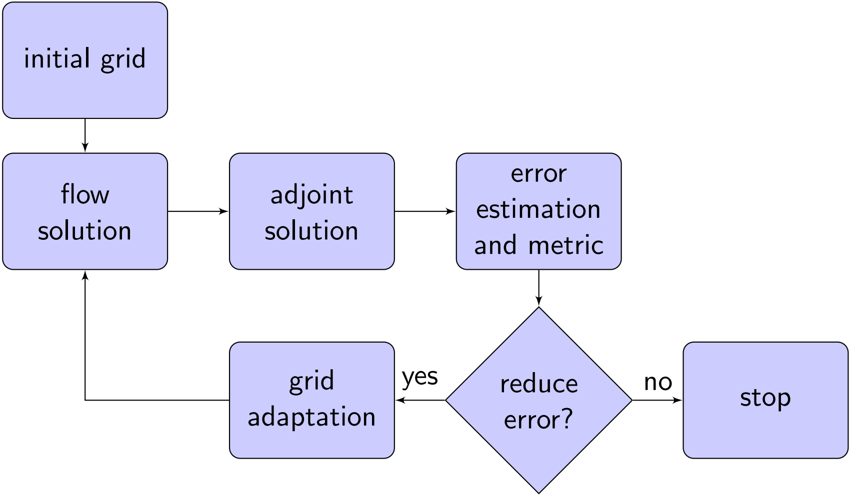
- 3D analytic-metric adaptation for a planar geometry and simple curved surface CAD model
- Creation of a benchmark repository and website

Today's SciTech Talk: 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

Integrated Grid Adaptation Process



First step: examine grid adaptation mechanics

Outline

Metric Conformity

Background

- Isolates the grid adaptation mechanics from the other elements of an integrated process
- Enables grid adaptation research without the need of developing and verifying the entire process

Inputs

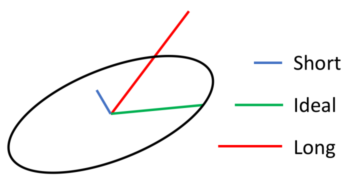
- STEP, IGES, and EGADS (Electronic Geometry Aircraft Design System) formats available for geometry description
- Grid and metric pairs extracted from a cycle of grid adaptation

Outputs

- Adapted grid and interpolated input metric provided for evaluation

Metric Conformity Evaluation

Edge Length in Metric Visualized as an Ellipse



Measures

- Edge length evaluated in metric
- Element mean ratio evaluated in metric $C \frac{Vol^{2/3}}{\sqrt{\Sigma EdgeLength^2}}$
- Both measures are unity in the ideal case

Descriptive Statistics

- Histograms

Methods

Omega_h

- Rensselaer Polytechnic Institute and Sandia National Laboratories
- Insertion, collapse, swap, and node movement for incremental projection

Pragmatic

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

Methods

EPIC

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

refine

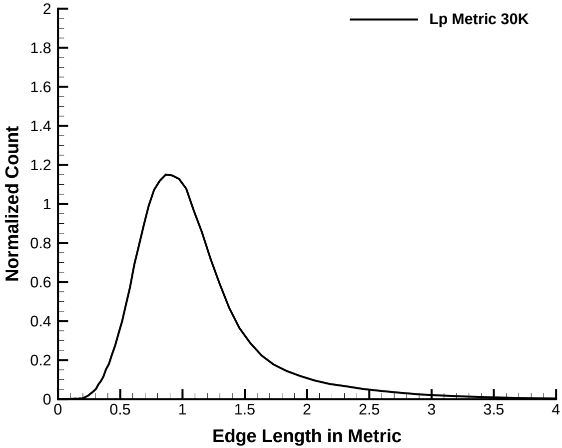
- NASA
- Insertion, collapse, and node movement

Feflo.a

- INRIA
- Cavity-based operator

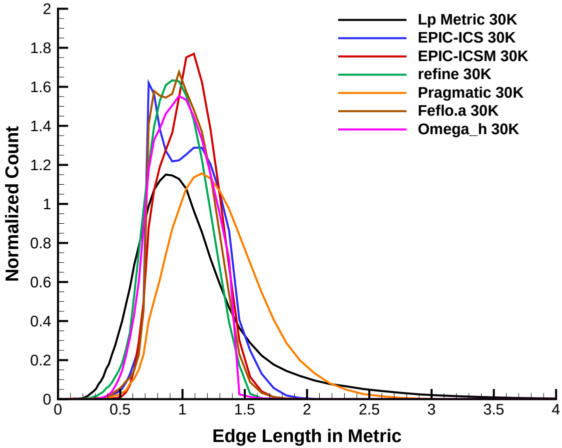
ONERA M6 Metric Conformity Descriptive Statistics

Edge length distribution, given metric on input grid



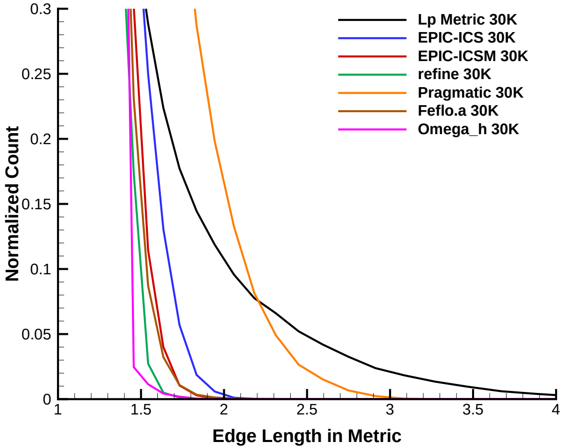
ONERA M6 Metric Conformity Descriptive Statistics

Edge length distribution, adapted grids



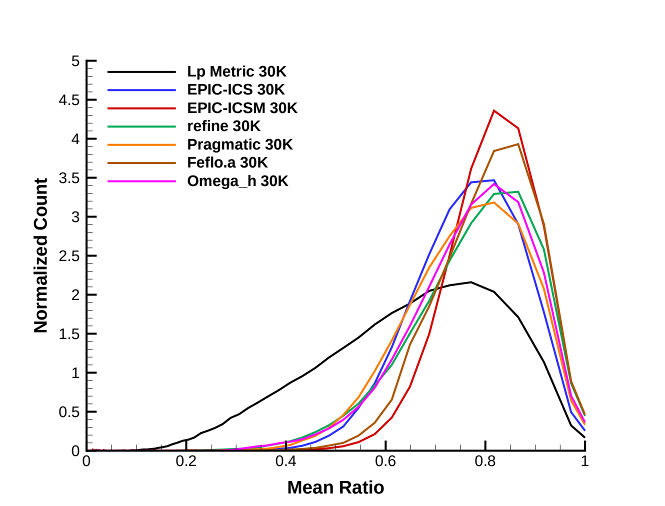
ONERA M6 Metric Conformity Descriptive Statistics

Edge length distribution tail, adapted grids



ONERA M6 Metric Conformity Descriptive Statistics

Mean ratio, adapted grids



Metric Conformity Descriptive Statistics

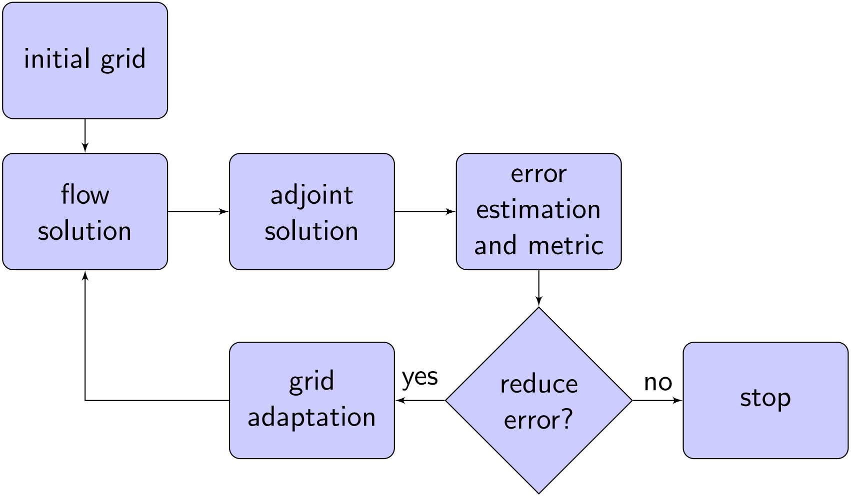
Section Summary

- Two grid-metric pairs for Hemisphere Cylinder and ONERA M6
- These four cases with metric interpolation are a clear extension of the analytic metric cases in previous evaluations
- Unstructured to the wall, valid, and boundary conforming to CAD
- All methods improved the input grids
- Trade-offs between peak of the distribution and the tails discussed in paper
- Log-scale plots in paper examine tails of distribution
- Motivates a closer examination of each operator (insertion, node movement, . . .)
- How are computable measures related to flow solver performance?

Outline

1. Motivation and Introduction
2. Metric Conformity of Grid Adaptation Mechanics
3. **Evaluating Integrated Grid Adaptation Processes**
4. Summary and Conclusions

Integrated Grid Adaptation Process



Integrated Grid Adaptation Processes

GGNS+EPIC-ICS

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

FUN3D-FV+refine

- NASA
- Upwind finite-volume method

Wolf+Feflo.a

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

Metrics

Mach-L_p

- Recovered Mach Hessian, scaled to control L_p ($p = 2, 4$) norm of interpolation error at specified complexity (adapted grid size)
- Theory and experiments show second-order interpolation error control
- Different from other Hessian and feature-based schemes

Output-based or goal-oriented

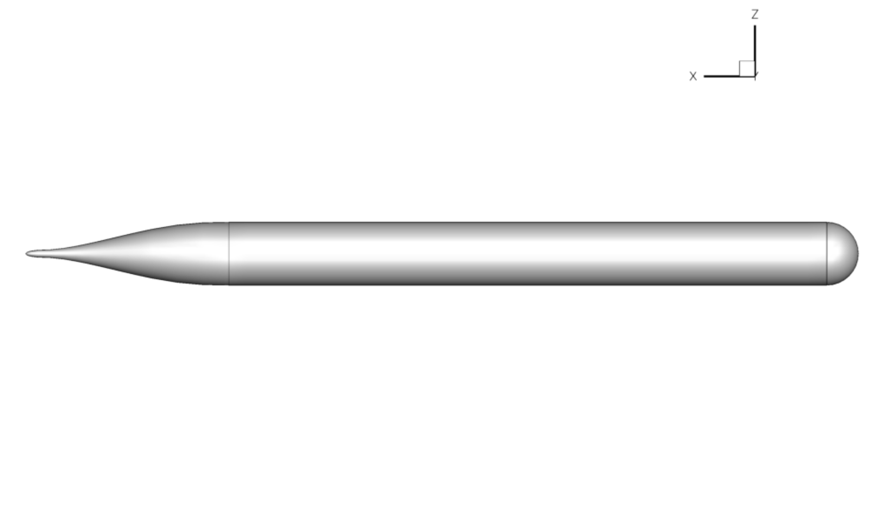
- Includes adjoint to control estimated error in output (lift, drag)

Inputs

- STEP, IGES, and EGADS (Electronic Geometry Aircraft Design System) formats available for geometry description
- Extremely coarse initial grids (based on curvature, no refinement for physics or boundary layer)

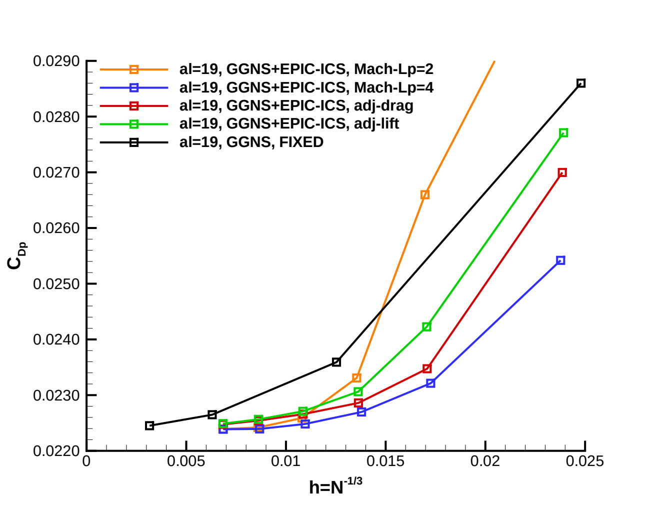
Aft Closure - 3D Hemisphere Cylinder

Geometry



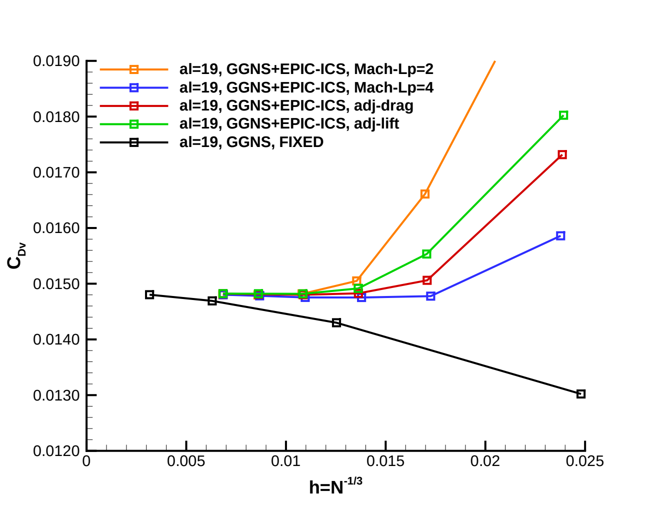
Aft Closure - 3D Hemisphere Cylinder, 0.6 Mach, 350,000 Re(D), 19° AoA

GGNS+EPIC-ICS pressure component of drag coefficient



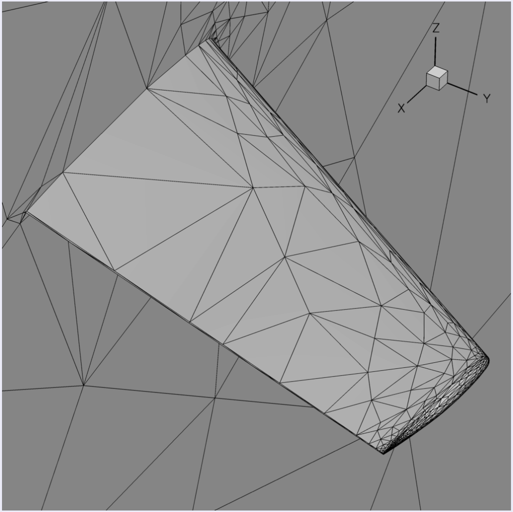
Aft Closure - 3D Hemisphere Cylinder, 0.6 Mach, 350,000 Re(D), 19° AoA

GGNS+EPIC-ICS viscous component of drag coefficient



ONERA M6

Curvature resolving initial grid without boundary layer refinement



ONERA M6

Verify Mach-L_p metric

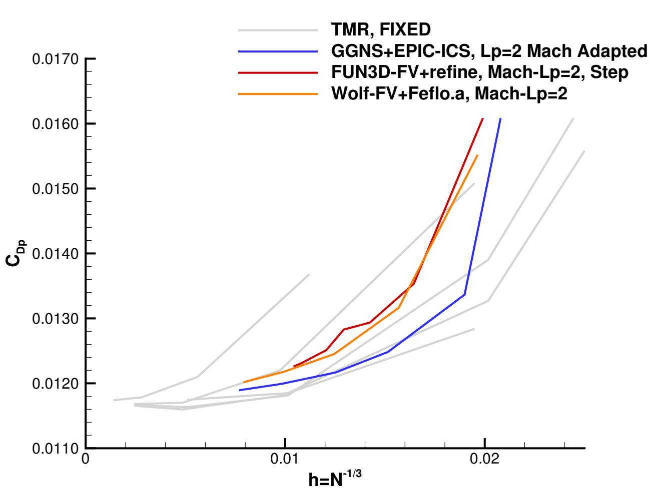
- GGNS+EPIC-ICS
- FUN3D-FV+refine
- Wolf+Feflo.a

Flow solver code-to-code comparisons on adapted grids

- GGNS+EPIC-ICS lift output-adapted grids
- FUN3D-FV
- Wolf

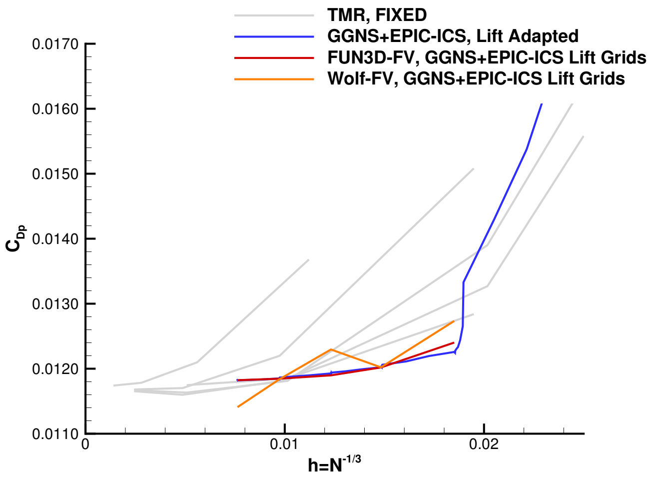
ONERA M6, 0.84 Mach, 14.6M Re(Root), 3.06° AoA

Pressure component of drag coefficient



ONERA M6, 0.84 Mach, 14.6M Re(Root), 3.06° AoA

Pressure component of drag coefficient



Outline

In Paper

- Additional metric conformity and integrated adaptation process details and results
- Proposal for persisting discrete grid association to CAD
- Description of interchange file formats that allow evaluation
- Accurate wall distance was critical to results, adapted grids violated an assumption in standard FUN3D-FV wall distance method

Summary

Metric Conformity

- All methods improved the metric conformity of input grids
- Unstructured to the wall, valid, and boundary conforming to CAD
- Improvements to five grid adaptation mechanic implementations demonstrated over previous benchmark

Integrated Grid Adaptation Processes

- GGNS+EPIC-ICS consistently approached uniformly-refined grids
- Mach interpolation error L_p metric was accurate, output better
- FUN3D-FV and Wolf was more accurate on GGNS+EPIC-ICS adapted grids than FUN3D-FV+refine and Wolf+Feflo.a adaptive processes
- More work required to verify metric construction and integrated processes

Conclusions

Unstructured Grid Adaptation Progress

- Marked increase in the complexity of the flow physics, adaptive metric, and geometry in grid adaption code-to-code verification
- $\mathcal{O}(1000)$ valid, metric-conforming, and boundary-conforming adaptive grids
- Demonstrated CFD Vision 2030 and AIAA-2016-3323 time-line elements

Next Steps and Recommendations

- Examine individual steps used to assemble L_p (and output) metrics
- Provide unstructured adapted grids to all solver groups in the next Solver Technology Special Session
- How are computable grid-metric measures related to flow solver performance?

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)
- Metric interpretation and adaptive mechanics on curved geometries
- Accept issues present in typical CAD geometries
- Adaptive curved grids for higher-order schemes
- Efficiency on current and emerging high performance computing platforms
- Evaluation of individual local grid operators in isolation

Adaptive grid computations displace fixed grids as the default

- Technology diffusion strategy for verified methods
- Partnership with commercial entities

Unstructured Grid Adaptation Working Group (UGAWG)

https://UGAWG.GitHub.io

- Documentation is sparse, but will be improved based on community feedback
- Grids and metrics available for analysis or developing new methods
- Define new test cases and evaluation methods

Join virtual meetings

- UGAWG@Mail.EmailHorse.com or Mike.Park@NASA.gov
- Understand the impact of implementation details and plan publication

Benefits of implementation discussions

- Published references are often incomplete (page limits favor brevity)
- Why a particular implementation was chosen is omitted
- Less successful approaches are not documented

Backup Slides

Wall Distance Calculation

Accurate wall distance critical for Spalart-Allmaras and other turbulence models

Standard FUN3D-FV wall distance method

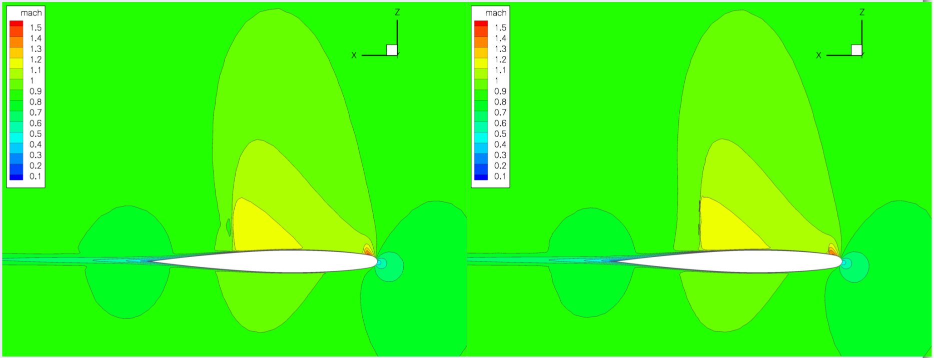
- Assumes that the closest boundary triangle is adjacent to closest boundary node.
- Good assumption for orthogonal grids, but not sufficient for completely unstructured anisotropic volume and surface grids

Alternate wall distance method

- Tree search of triangles

ONERA M6 GGNS+EPIC-ICS L_p Grid

Mach slice, GGNS and FUN3D-FV with alternate wall distance



ONERA M6 GGNS+EPIC-ICS L_p Grid

Mach slice, FUN3D-FV with standard and alternate wall distance