Enhancement of Applied Aerodynamics Simulations Using Adaptive Mesh Refinement

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Outline

Introduction

Generalized AMR Best Practices

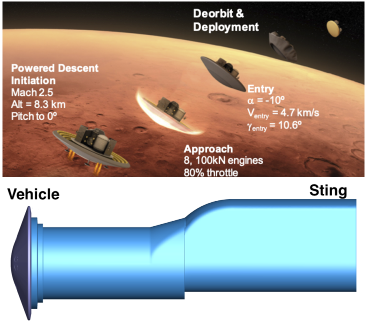
1. Off-body AMR Box
2. Near-body AMR
3. High-Frequency AMR
4. Refinement Level Selection

Summary

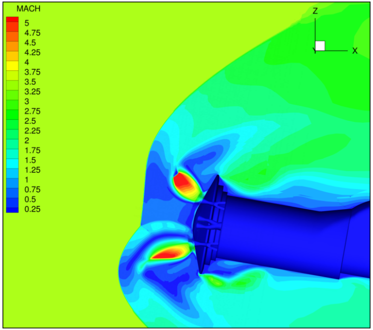
Motivation

Accurate modeling of complex flows requires both fine and specific grid distribution

- Modeling example: Wind tunnel-analogous Supersonic Retropropulsion (SRP)
  - Complex shock-plume interaction, significant variation with time
  - AMR can achieve grid design requirements efficiently and automatically
- **Objective: establish best practices for flow modeling using generalized AMR**



HIAD low-L/D Mars EDL concept [1]
and OVERFLOW CFD model



CFD $y = 0$ flowfield Mach

Background

OVERFLOW provides a robust AMR implementation for overset grids [2]

- Near- and off-body grid adaption based on solution error (gradients)
- Recent AMR improvements (essential for production CFD):
  - Data extraction (witness) grid compatibility with AMR
  - Solution averaging with AMR (large-sample solution averaging)

Advantages of generalized AMR for production CFD

- Automatic grid refinement “capturing” of flow-specific phenomena
- Automatic grid optimization to specific flow condition
- Reduced user overhead during grid design process (faster product turnaround)

Generalized AMR requires fundamental best practices for overset grids

- Well-conditioned overset connectivity (no orphan points)
- Quality overlap for accurate communication between grids
- Baseline, small-scale refinement near surface for boundary layer modeling

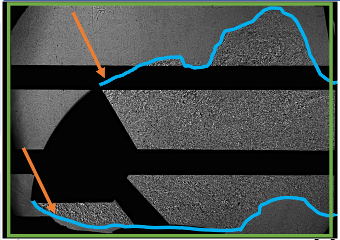
Production CFD with Generalized AMR

Production CFD examples

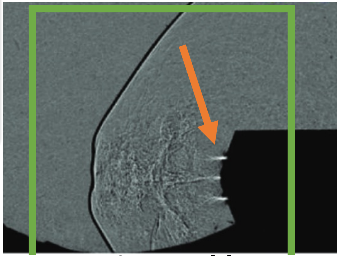
- Blunt-body Crew Module (CM) flow
- Supersonic retropropulsion (SRP) for Mars EDL

Best practices for generalized AMR

1. Resolve off-body flow on overset "AMR-box" (e.g. wake)
2. Resolve near-body flow with AMR in body grids (e.g. BL)
3. Use high adaption frequency for unsteady flows
4. Use AMR level where solution independent of mesh size
5. Ensure sufficient resolution of witness grids (relative to AMR)



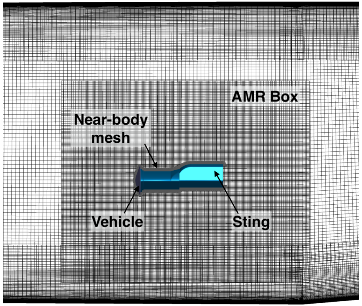
Orion CM shearlayer separation [3]



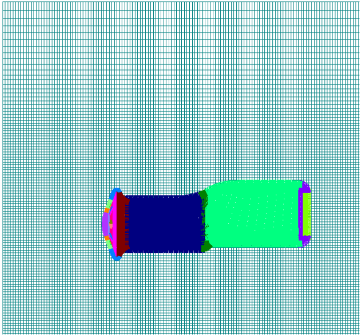
SRP flow [4]

Outline for Section 2

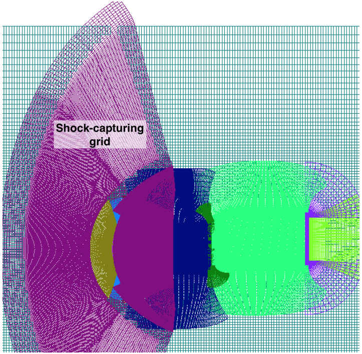
1. Resolve Off-body Flow on AMR Box



Generalized AMR box overlaid on near-body volume grid



Generalized AMR box



Traditional "capturing" grids

Overlaid coarse box allows mesh refinement of off-body flow features

- AMR box must encompass entire volume where dominant flow features will develop
  - e.g. bow shock, shock-plume interaction, separated wake, etc.
- Eliminates need for traditional, manually-designed "capturing" grids
  - Reduced user-overhead, better optimized to multiple flow conditions

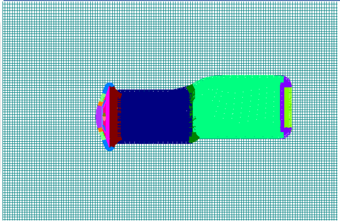
Design of Baseline (Unrefined) AMR Box

Use coarse baseline resolution

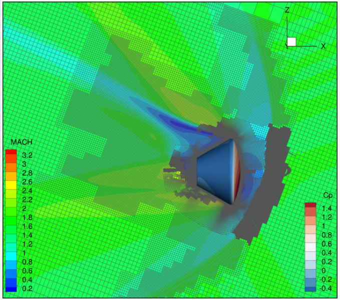
- AMR provides fine mesh resolution only where needed
- Reduces overall size of final grid system
- Note: Box refinement *must* match near-body at overlap

Tune baseline grid topology to specific flow requirements

- AMR in OVERFLOW is isotropic. . .
- . . . AMR will reflect *original* grid cell alignment and isotropy
- **Multiple AMR boxes for competing topology needs**:
  1. Wake AMR box: fine, isotropic cells (resolve separated SL)
  2. Shock AMR box: anisotropic and aligned cells (smooth shock)



Generalized AMR box (for SRP)



Additional AMR box for CM bow shock*
* (Idealized, non-flight heatshield geometry)

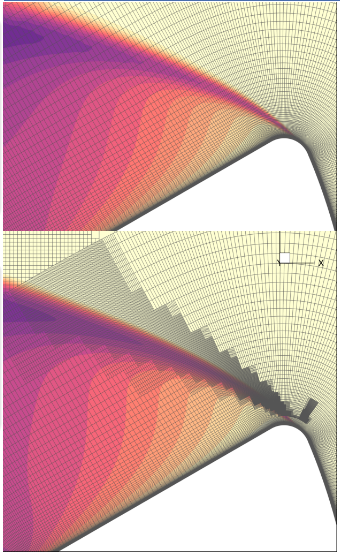
2. Refine Near-body Flow With AMR

AMR in near-body improves boundary layer modeling

- Baseline near-body grid refinement may be inadequate due to limitations of structured grids
- AMR better-resolves shear layer separation
- Provides additional refinement of transonic phenomena

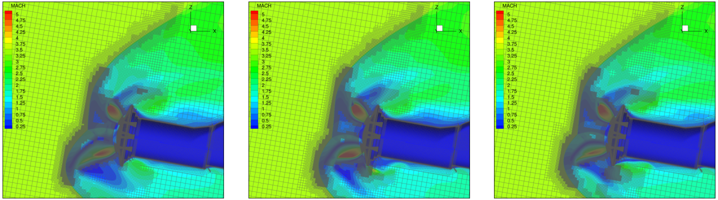
Avoid AMR <u>on</u> grid surface (from L=1 to L=10-20)

- Preserves designed $y^+ \approx 1$
- Preserves interpolation to witness grids (e.g. pressure taps)
- Implementation: AMR limit regions in L-direction



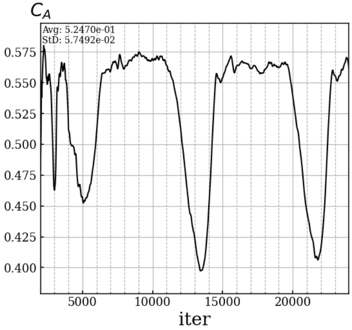
CM shear layer TKE (idealized geometry)
(Baseline/AMR LVL 2, top/bottom)

3. Adapt Mesh at High Frequency



(a) $i = 12500$ (b) $i = 16000$ (c) $i = 18000$

Time-varying, "chugging" plume oscillation



Heatshield axial load

Resolve flow unsteadiness with high-frequency adaption

- Set adaption frequency $NADAPT >$ unsteady flow time scales
- Confirm that grid refinement updates to always contain important flow features
- SRP example: Dynamic AMR tracks unsteady shock-plume interactions, strong influence on heatshield pressure distribution

4. Refine to Solution Mesh-Independence

Determine production AMR refinement level

1. Refine AMR grids to successively finer levels
2. Observe when integrated loads asymptote W.R.T. AMR LVL
3. Use AMR LVL with good recovery of asymptotic accuracy

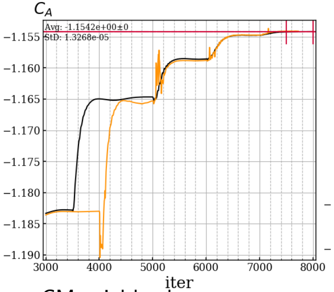
(Note: DT refinement study should accompany ΔX study)

Quantification of uncertainty due to (AMR) mesh resolution

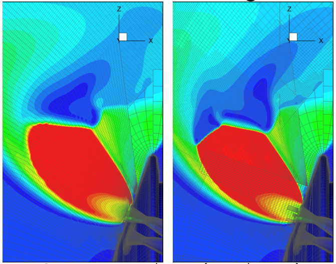
- Difference between production LVL and true asymptote
- Study can be performed on every CFD case (if desired)
- Improve efficiency: baseline resolution/size trade study

SRP flow example of AMR mesh convergence

- Final plume shock structure is only resolved for AMR LVL ≥ 2



CM axial load convergence



SRP coarse/fine (left/right)

Outline for Section 3

Generalized AMR Best Practices

Procedure to enable an overset grid system for generalized AMR resolution of critical, flow-specific features

1. Resolve off-body flow on overset AMR-box
   - Box encloses all significant flow phenomena (e.g. oscillating wake, bow shock, etc.)
   - Coarse initial resolution achieves efficient domain refinement (only where needed)
   - Box/Body grid overlap must have comparable cell size for accurate communication
   - Design grid topology (cell isotropy/alignment) to specific flow application
2. Resolve near-body flow with AMR in body grids
   - Further refine mesh resolving boundary layer unsteadiness & transonic flow
   - Avoid AMR on surfaces to preserve y^+, witness grid interpolation stencils
3. Use Dynamic AMR (high-frequency adaption)
   - Set adaption frequency greater than unsteady time scales of the flow
   - Confirm important flow features are always contained by sufficient mesh resolution

Generalized AMR Best Practices, Cont.

Procedure to enable an overset grid system for generalized AMR resolution of critical, flow-specific features

4. Determine refinement level where solution is independent of mesh resolution

- Compare integrated loads at successive levels of AMR
- Choose production AMR LVL to reasonably recover asymptotic convergence

5. Grid instrumentation/Data extraction

- Design witness grid resolution based on final AMR level
  - (prevent information loss by coarse interpolation)
- Long-sample solution averaging:
  1. Each saved solution is for a unique AMR grid
  2. Create a single target grid (all AMR grids full-refined to resolution for post-processing)
  3. Map solution averages to target grid and concatenate to a single long-term average

Best practices for generalized AMR are under continued development

- Generalized AMR has successfully improved production CFD processes for:
  - Orion capsule CFD database development and high-fidelity DES analysis
  - Pre-test predictions of SRP flow over DSS HIAD and CobraMRV concepts

Questions?

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