Automated High Fidelity Simulation

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Computational Fluid Dynamics (CFD)

CFD in aerospace engineering

- Numerous codes in private and public sector
- Actively used in design and analysis
- Supplements or replaces expensive wind-tunnel tests
- Reduces design cycle time
- Meshing relies on expert judgment

Typical Design Process:

1. Computer-Aided Design (CAD) Geometry
2. Discrete Computational Mesh
3. Flow Solution
4. Error Estimate, Adaptive Indicator

Weeks

Hours/Days
Description

- Geometries: DLR-F4 WB and DLR-F6 WB / WBNP
- Case: $M_\infty = 0.75$, $C_L = 0.5$, $Re = 3 \times 10^6$, fully turbulent
- Grids: $\sim 3 \times 10^6$ (DPW I), $\sim 1 - 10 \times 10^6$ nodes (DPW II)
- $\sim 25$ participants, $\sim 20$ codes

Results [Levy et al., 2003; Hemsch and Morrison, 2004]

- Code-to-code scatter very large: $\approx 40$ drag counts ignoring outliers (DPW I)
- No discernible reduction in scatter with grid refinement (DPW II)
- Asymptotic rates not achieved with grid refinement (DPW II)
Further Results

Mavriplis demonstrated uniform refinement of different mesh topologies (UW versus CESSNA topology) apparently converging to different lift ($C_L$) estimates even with meshes having many more elements ($N$) than typically used in practice.

Mavriplis, 2007

“The range of scales inherent in computational aerodynamics problems... make it unfeasible to fully resolve all regions of the computational domain through successive global refinements of an arbitrarily constructed initial grid...”
Next-Generation CFD

Project X

Research initiative at Aerospace Computational Design Laboratory aimed at developing the next generation CFD capability.

Goal:

Engineering accuracy in a reasonable amount of time and in an automated manner.

Outcome:

Desired outcome: let engineers be engineers not meshing experts.

Enabling Features:

- Solution-based adaptivity
- Higher-order discretization
- Direct interface to Computer-Aided Design (CAD) models
Enabling Feature: Output-Based Adaptation

$C_D = 565.7 \text{ counts}$

- How accurate is this value?
- Where is more resolution necessary to improve the accuracy?
Output Error Estimation: The Adjoint

- Given a governing equation with a source term \( g \), a solution \( u \) and a functional output, \( J \),

\[
\nabla \cdot F(u) = g(x), \quad J(u(g))
\]

- The adjoint, \( \psi \), is a Green’s function relating the output sensitivity to the source term,

\[
J(u(g)) - J(u(0)) = \int_{\Omega} \psi g(x)
\]

- For error estimation and adaptation, \( g \) is the truncation error.

- For gradient-based design optimization, \( g \) is the residual perturbation due to design variable perturbation.
The adjoint, $\psi$, is a Green’s function relating the output sensitivity to the source term,

$$\mathcal{J}(u(g)) - \mathcal{J}(u(0)) = \int_\Omega \psi g(x)$$
Adaptive Algorithm

**Idea:** refine elements with high error; coarsen elements with low error

- Solve primal and dual equations on current mesh.
- Estimate output error and element contributions.
- Find desired mesh size in each existing element using an *a priori* output error estimate to relate element error to size request:
  \[ h_{\kappa} = h_{\kappa}(\epsilon_{\kappa}) \]
- Adapt mesh
Examples of Output-based Adaptation

- High-lift, multi-element airfoil
- Sonic boom application
- Nozzle Guide Vane missile (NASA Ames)
RANS drag adaptation example: EET Airfoil

Initial Mesh (11063 elements)

Final Mesh (11620 elements), $\rho = 3$ solution
EET Airfoil Results ($p = 3$)

Mach Number

Eddy Viscosity

Pressure Distribution

Outputs on final mesh

- $c_\ell = 3.51$ — agrees well with experiment and other computations
- $c_d = 436$ counts — error estimate = 3 counts
Supersonic flow
Farfield pressure adaptation

NACA 0012, $M_\infty = 2$, $Re = 10^4$, $\alpha = 0^\circ$

- Adaptation on $\int_{x_0}^{x_1} (p - p_\infty) \, dx$ on a line location 20 chords above airfoil
- Interpolation orders $p = 1–3$. 
Supersonic flow
Farfield pressure adaptation

Initial (all $p$)

Final $p = 1$

Final $p = 3$
Supersonic flow
Farfield pressure adaptation

Pressure signal convergence for $p = 2$

![Graph showing pressure signal convergence for different iterations.](image)
NGV Missile
Functional: Axial force

- Initial mesh: ~5k cells
- Supersonic flow: $M_\infty = 2$, $\alpha = 0^\circ$
- Power boundary conditions applied at plenum face

Fins and nozzle guide vanes

Near-body view of initial mesh

Nozzle cutaway
NGV Missile
Nozzle cutaway (6 adaptations, Mach contours)
Future Work

- Applications in other areas in particular internal flows
- Extensions to unsteady flows