

Physical Modeling & Geometry and Meshing Advancements Toward CFD Vision 2030

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Identified Technology Gaps and Impediments

CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences

- **Identified Technology Gaps**
  - **Physical Modeling { Turbulence Modeling }**
    - Lack of theoretically based hybrid RANS / LES
    - Availability of complex turbulence models in practical software
    - Grid resolution and solution scheme effects
    - Insufficient use of real-world experiments and foundation calibration datasets
    - Robust transition prediction
  - **Geometry and Mesh Generation**
    - Inadequate linkage with CAD
    - Poor mesh generation performance and robustness
    - With few exceptions, human-in-the-loop workflows continue to pace simulation performance
    - Lack of scalable CFD pre- and post-processing methods (exa-scale)



Community Activities

Grand Challenge Problems and Workshops serve as visible evidence of progress towards the CFD Vision

Grand Challenges

- Complete Aircraft High Fidelity (LES simulation) Across Entire Flight Envelop
- High Lift Aerodynamics
- Full-engine CFD simulation
- Hypersonic Modeling and Simulation
- CFD-in-the-Loop Monte Carlo Flight Simulation for Space Vehicle Design
- Certification by Analysis Uncertainty Quantification

AIAA Workshops

- Drag Prediction
- High Lift Prediction
- Sonic Boom Prediction
- Computational Aeroacoustics
- Geometry and Mesh Generation
- Propulsion Aerodynamics

AIAA Technical Committees

- Aeroacoustics
- Applied Aerodynamics
- Fluid Dynamics
- Inlets, Nozzles and Propulsion Systems Integration
- Meshing, Visualization, Computation Environments



Progress in Physical Modeling – RANS / ML

RANS Modeling

- Progress has slowed – mostly model enhancements to extend range of applicability
- RS Closure models have not reached routine application – marginal improvements for additional computational effort (2023 Milestone)
- Advances in developing adaptive modeling approaches that preserve agreement with canonical flows but enable adjustable parameters to match empirical separation data
  - GEKO (Menter)
  - Constrained Recalibration (Bin, Huang, Kunz, Yang)

Machine Learning for Turbulence Modeling

- Significant activity – hope for a modeling breakthrough
- Fully data driven approaches have been relatively ineffective
  - Can violate established turbulent canonical flows
  - Training and inference can be computationally intensive
- Field Inversion Machine Learning (FIML) – demonstrated on moderately complex cases
  - Show promise but can violate established turbulence relations
  - Can provide a poor model without sufficient data
- Promise for ML training of constrained models (GEK0-type)



Progress in Physical Modeling – Scale Resolving Methods

Wall Resolved (WRLES)

- Computational capacity has enabled extreme levels of complexity and resolution for frontier applications
  - 865B DOF for high pressure turbine
  - 100B for open fan blade
- Useful for fundamental flowfield investigation, but impractical for engineering design

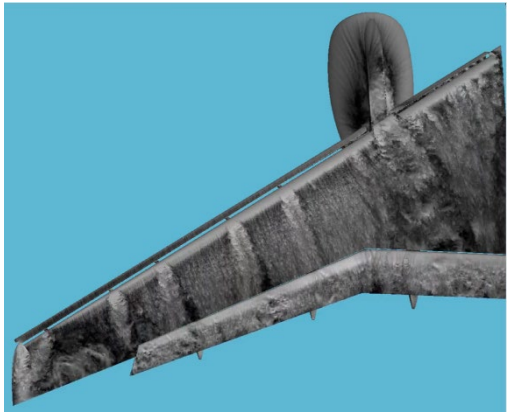
Wall Modeled LES (WMLES)

- Significant demonstrated progress on High Lift Configuration
  - Significantly improved accuracy, both approaches compared to RANS in flows with large regions of separation
  - Challenges remain for accurate prediction of smooth body separation
- WMLES is less accurate in less challenging, mostly attached flow application than RANS

PROJECTION

Scale resolving methods applications will continue to grow

- GPU HPC systems enable expanded use with reasonable turnaround
- Improved modeling approaches for WMLES will enable more predictive capability
- WRLES and DNS on frontier problems reveal flow physics, enable new modeling approaches incl. ML



WMLES simulation of JAXA JSM



Progress in Physical Modeling – Roadmap TRL

		TRL key	0	1	2	3	4	5	6	7	8	9
			2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Physical Modeling													
RANS													
Improved RST models in CFD codes	2016		7	7	7	7	7						
Integrated transition prediction (Tollmein-Schlichting modeling)	2017		6	6	6	6	6						
Integrated transition prediction (non-TS)	2027		3	3	4	4	4						
Highly accurate RST models for flow separation	2025		2	2	2	2	3						
Demonstration of machine learning to simulation of complex flow regime	2025		1	3	4	4	4						
Hybrid RANS/LES													
Integrated transition prediction	2025		2	2	2	2	2						
Unsteady, complex geometry, separated flow at flight Reynolds number (e.g., high lift)	2023		4	4	5	5	5						
LES													
Integrated transition prediction	2025		2	2	2	2	2						
WMLES/WRLES for complex 3D flows at appropriate Re	2023		5	5	5	5	5						
Unsteady, 3D geometry, separated flow (e.g., rotating turbomachinery with reactions)	2027		3	3	3	3	4						
Combustion													
Chemical kinetics calculation speedup	2017		3	3	3	3	3						
Chemical kinetics in LES	2021		4	4	4	4	4						
Multiregime turbulence-chemistry interaction model	2025		3	3	3	3	3						
Unsteady, 3D geometry, separated flow (e.g., rotating turbomachinery with reactions)	2027		3	3	3	3	4						



Progress in Geometry and Meshing - HLPW-4 / GMGW-3 (2022)

Current CFD Technology Unsuited to Low-Speed High-Lift Prediction, Why?

Technology Focus Groups

Mesh generation and flow-solver experts **work together** to accelerate advancement of methodologies particular to key questions from HLPW3.

- Fixed grid and adaptive grid RANS
- High-Order discretization
- Hybrid RANS/LES
- Wall-modeled LES and Lattice-Boltzmann

Outcome

- Despite increased geometric fidelity, participant review of the geometry model was highly positive. **Still, geometry preparation for analysis (meshing) remained a largely manual and subjective task.**
- Nearly 170 different meshes of the CRM-HL (**significant meshing throughput increase**)
- Level E meshes (1B+ cells), intended to demonstrate mesh-convergence, were **unable to be used due to resource restrictions**.
- Adaptive and scale-resolving results indicate **fixed-grid guidelines are insufficient near stall**.
- In the RANS cohort, **HO and adapted mesh results showed the least scatter** and better mesh convergence
- **Massively parallel meshing algorithms for WMLES**
  - Octree with immersed boundaries, clipped-Voronoi
- AVIATION 2022 contained 20+ papers on the workshops

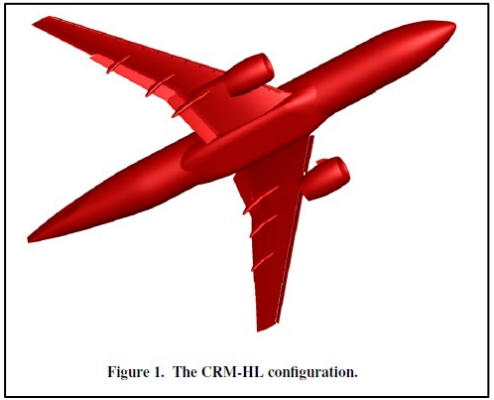
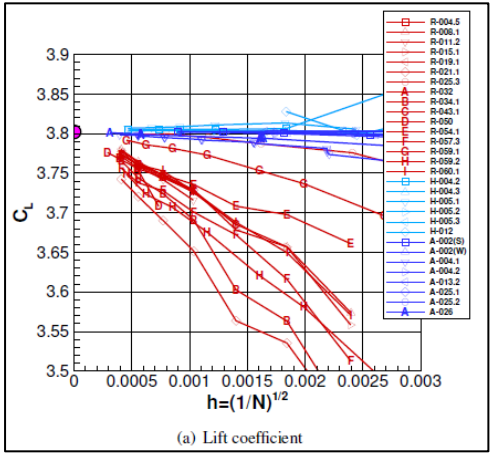


Figure 1. The CRM-HL configuration.



(a) Lift coefficient



Progress in Geometry and Meshing - HLPW-5 (2024)

Progress in Geometry and Meshing

CRM-HL Wing-Body Verification

- Single geometry, four mesh family

CRM-HL Configuration Build-Up

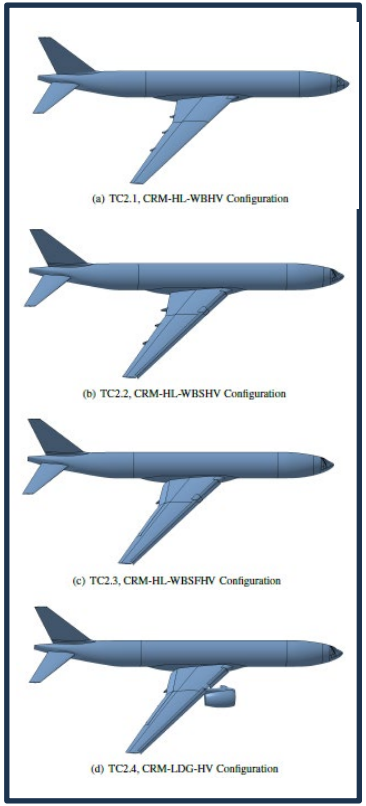
- Four increasingly complex models, four mesh family for each model

CRM-HL Reynolds Number Study

- Single geometry, four Reynolds Numbers, four mesh family for each Re

Workshop Assessment

Geometry preparation and fixed-grid RANS meshing are an automatable, robust process





Progress in Geometry and Meshing – Roadmap TRL

		TRL key	0	1	2	3	4	5	6	7	8	9
			2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Geometry Modeling and Mesh Generation													
Geometry Modeling													
Quantified, reversible data transfer demonstrated between opaque and open geometry model representations.	2023		5	5	5	5	5						
Associative equivalence demonstrated for OML manipulation schemes.	2025		0	3	3	3	3						
Distributed, open geometry representation platform established	2027		0	2	2	2	2						
Robust, quantifiable multidisciplinary data exchange supported by open data standard.	2029		0	2	2	2	2						
HPC Meshing													
Large-scale parallel mesh generation	2020		5	5	5	5	5						
Generate a 100 billion cell, fit-for-purpose volume mesh.	2025		1	1	1	1	1						
Generate a 1 trillion cell, fit-for-purpose volume mesh.	2030		1	1	1	1	1						
Fixed Meshing													
Tighter CAD coupling	2015		9	9	9	9	9						
CAD coupling available in commercial grid generation	2023		5	5	5	5	5						
Automatic generation of suitable mesh on complex geometry on 1st attempt.	2021		4	4	4	4	4						
Automatic generation of a family of meshes about a complex configuration.	2023		4	4	4	4	4						
Adaptive Grid													
Production AMR in CFD codes	2016		5	5	5	5	5						
Adaptive meshing techniques will accept typical assembly tolerance levels and unfavorable B-Rep topologies to accept a pragmatic interpretation of geometry.	2023		0	4	4	4	4						
Adaptive curved meshing to support higher-order solvers will be available from multiple implementations.	2026		0	3	3	3	3						
Accurate CFD solutions are verified by asymptotic convergence rate demonstration or low variation between independent implementations.	2028		0	3	3	3	3						
Adaptive mesh computations displace fixed meshes as the default and practitioners will rarely visualize the mesh directly.	2030		0	2	2	2	2						

Progress in Geometry and Meshing - Current Capability Gaps

Automation is not Universal

- HLPW5 successes attained on similar geometries and solution methodologies by groups of experts
- Automated geometry preparation (CAD-to-mesh) is immature and requires human intervention
- Suitable automatic meshing for other solution methods and physical problems remains unsolved
- Scale resolving simulation (e.g. geometry fidelity, local mesh resolution)
  - Hypersonics (e.g. solver robustness on arbitrary meshes)
  - Propulsion (e.g. film cooling, dynamic distortion)
  - Moving body problems (e.g. aeroelasticity, flutter)
- Barrier to entry for automation remains high – significant reliance on domain expertise

GPUs and the Commoditization of HPC

- Reduced CFD solution times heighten relevance of geometry and meshing performance
- Increased throughput allows greater geometric and aerodynamic database fidelity
- Optimization can be applied earlier in the design cycle
  - ***Design within your test and modeling capabilities***
  - Increased diversity of input to CFD workflows



Progress in Geometry and Meshing - Current Capability Gaps

Meshing Algorithm Improvements

- Meshing largely not scalable, not on the GPU
  - CPU-bound workflows with large data transfer overhead
- SRS mesh convergence?
  - 2024 INCITE award for grid refinement study at flight scale high-lift conditions
- WRLES requires competing blend of near-body anisotropic control with off-body scalability

Workflow Improvements

- Uncertainty quantification
  - ***Geometry is a first order effect***
    - Geometric sensitivity to design parameters
    - Geometric fidelity vs manufacturing tolerance
    - Computational geometry operator numerical error stability / bounds
- Simulation Data Management
  - ***Document model development and all assumptions***
  - Traceability, re-use under different requirements (configuration management)



Progress in Geometry and Meshing - Current Capability Gaps

Agentic AI

- Engineering analysis workflows are changing – are geometry and meshing tools ready?
- YES - In some respects
  - Natural language user interfaces improve user productivity
  - Automation tasks (scripts) authored by context-aware generative agents – *promise of universal automation*
  - *Helping us use existing tools more efficiently*
- But Perhaps NOT
  - Repeatability of agent generated workflows?
  - Generative design (automated design from requirements) is relatively unused in CFD workflows
  - Large financial investments may dictate workflows
    - Physical AI (Prometheus Project, SpaceX) versus Generative LLMs
  - Alternate geometry definitions (e.g. spatial occupancy, signed-distance field) may be required
  - *Helping us create more efficient designs*




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