# A STUDY ON FLOW SOLUTIONS COMPUTED ON AUTOMATICALLY AND MANUALLY GENERATED STRUCTURED OVERSET MESHES

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Advanced Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center, September 21, 2023

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# OUTLINE

- Update on overset mesh generation automation software

- Flow solution comparisons: automatically and manually generated meshes

  - Based on

    *Chuen, A. M., Hosseini, S. S., Jensen, J. C., Chan, W. M., Aerodynamic Simulations for Complex Geometries Using Automatically Generated Structured Overset Meshes, AIAA Paper 2023-3602, San Diego, CA, June, 2023.*

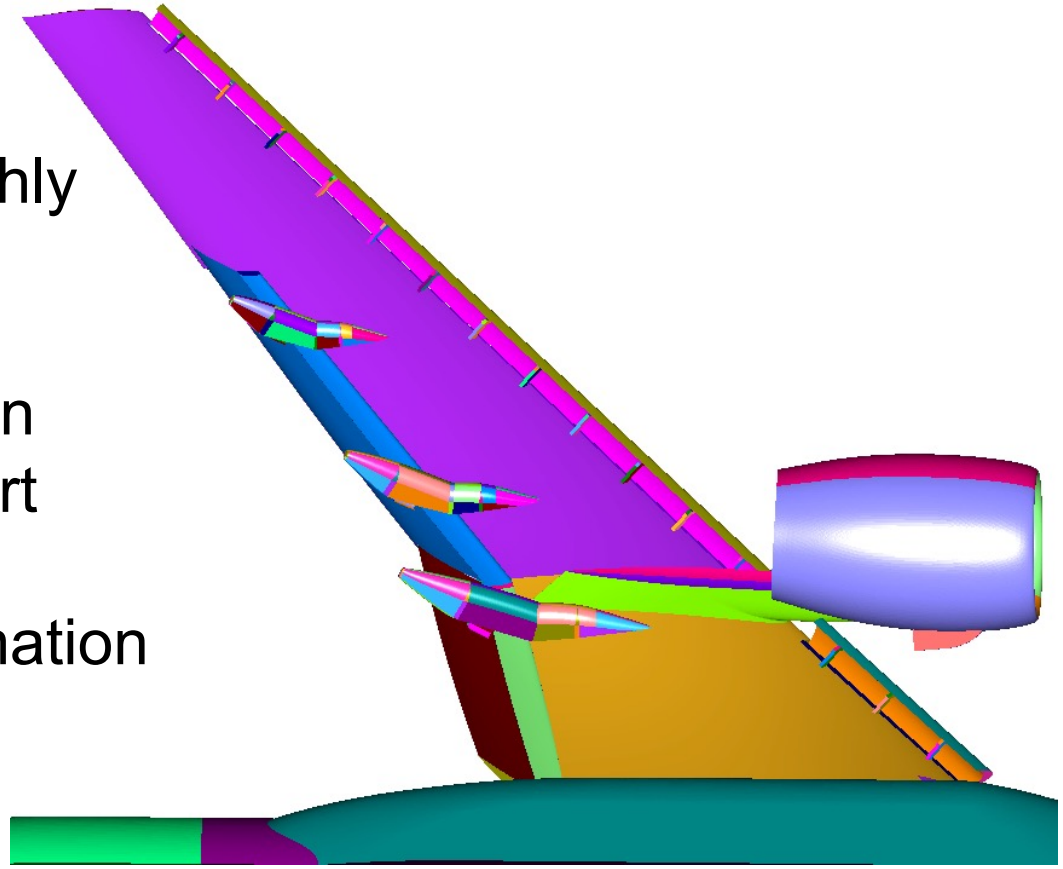
  - Progress since AIAA Aviation Forum 2023

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# OVERSET MESH GENERATION AUTOMATION LONG TERM GOAL

- Structured overset viscous flow solvers are highly accurate and efficient

- High-fidelity structured overset mesh generation
  - Requires significant user expertise and effort
  - Develop tools to speed up process
  - Significant time saving with 80 - 99% automation

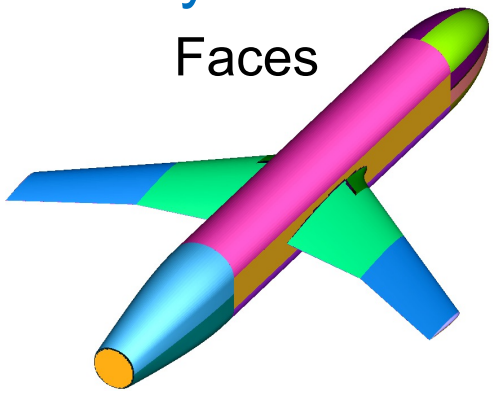


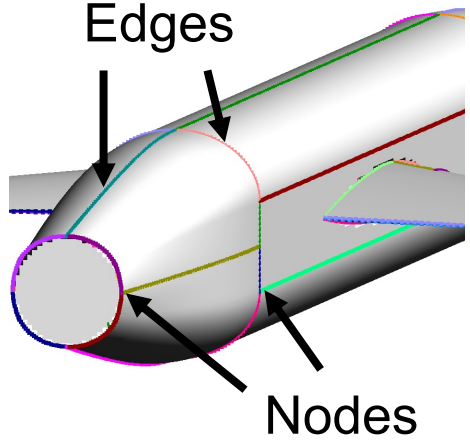
*Chan, W. M., Pandya, S. A., Chuen, A. M., Automation of Overset Structured Surface Mesh Generation on Boundary Representation Geometries, AIAA Paper 2022-3607, Chicago, IL, June, 2022.*

# OVERSET SURFACE MESH GENERATION AUTOMATION

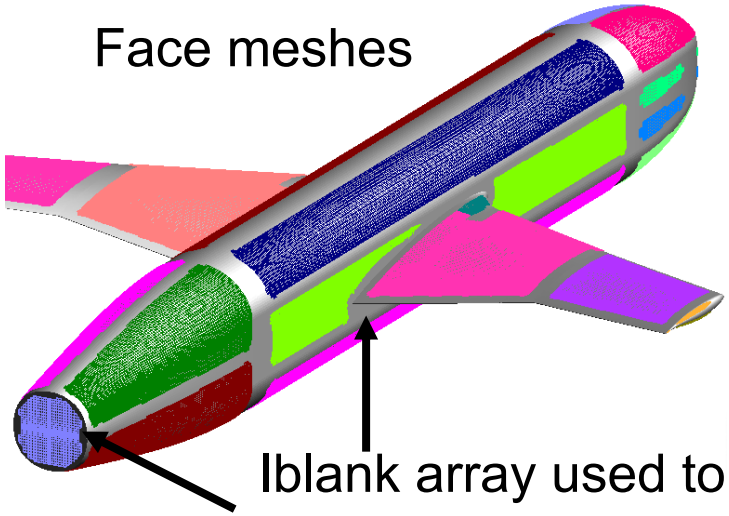
## Input Geometry

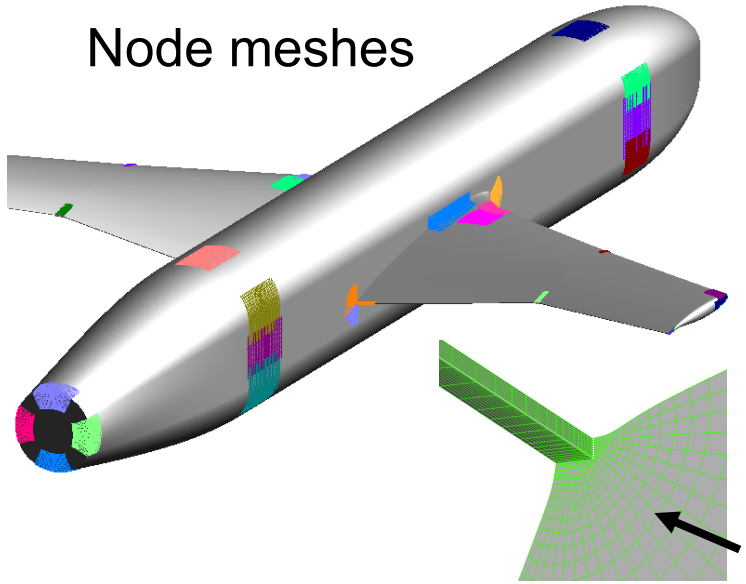
- Boundary Representation (BRep) solid
- Interface: Engineering Sketch Pad (ESP) from MIT

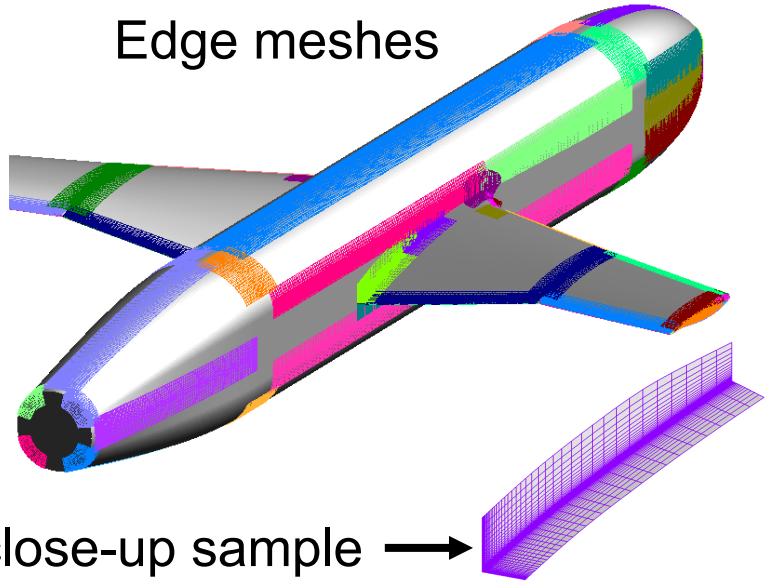



## Auto-Generated Meshes

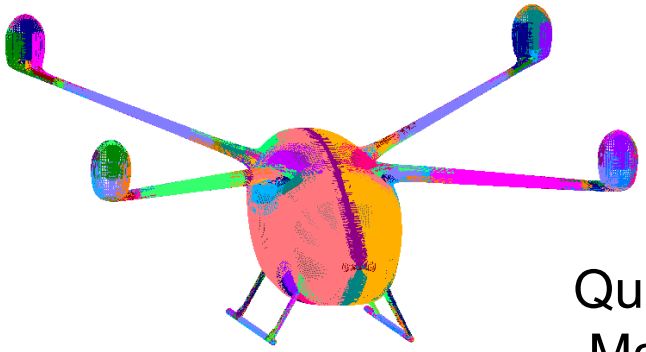


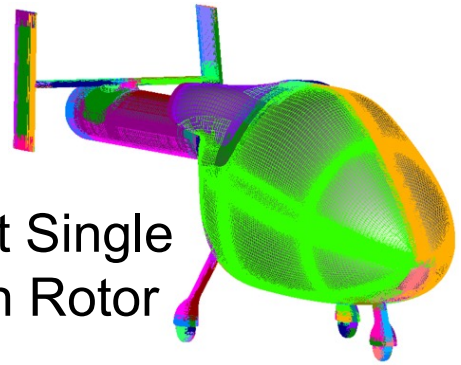



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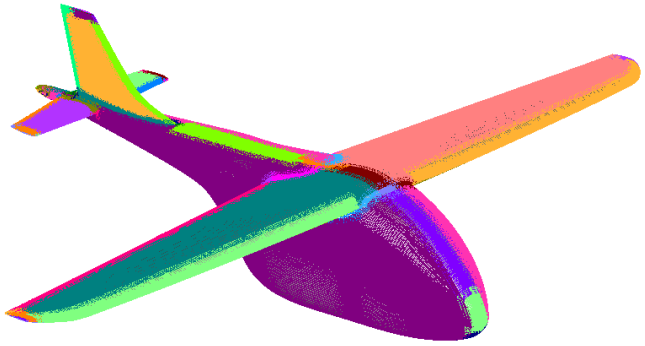
# SAMPLE TEST CASES



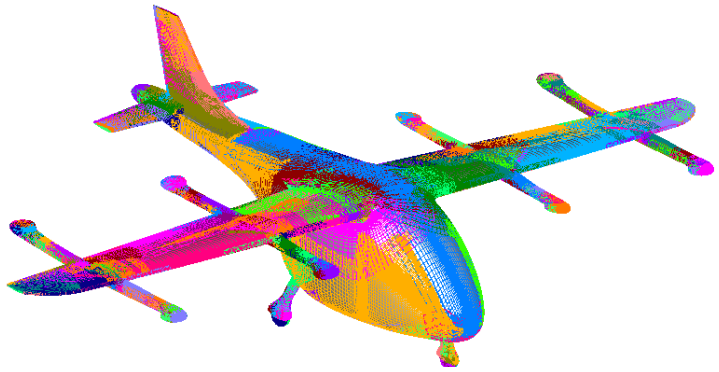
6-Pax Quadrotor



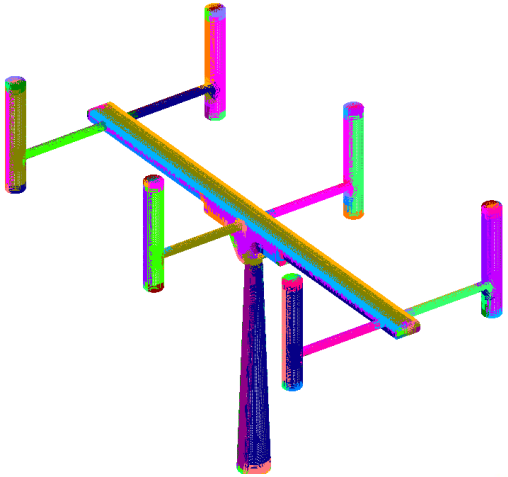
Quiet Single Main Rotor



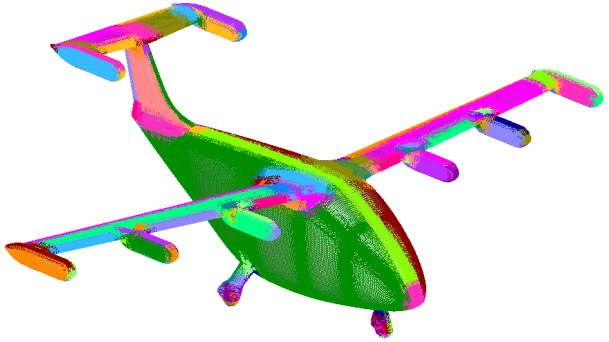
Lift+Cruise (no pylons, no gears)



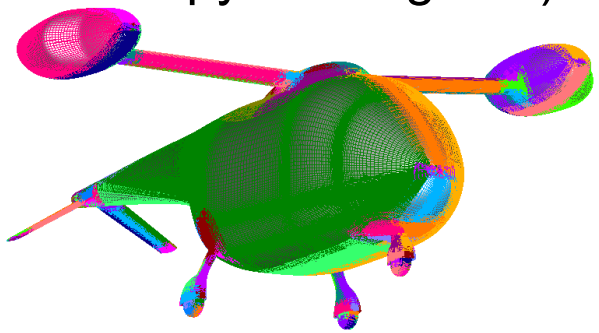
Lift+Cruise (with pylons & gears)



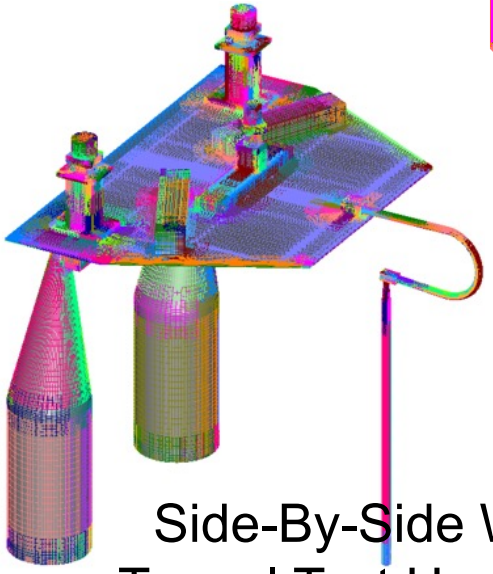
Multirotor Test Bed



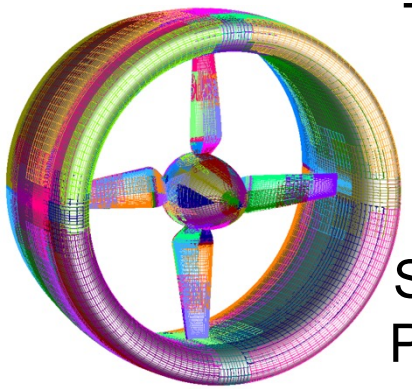
Tiltwing (cruise)



Side-By-Side Hybrid



Side-By-Side Wind Tunnel Test Hardware

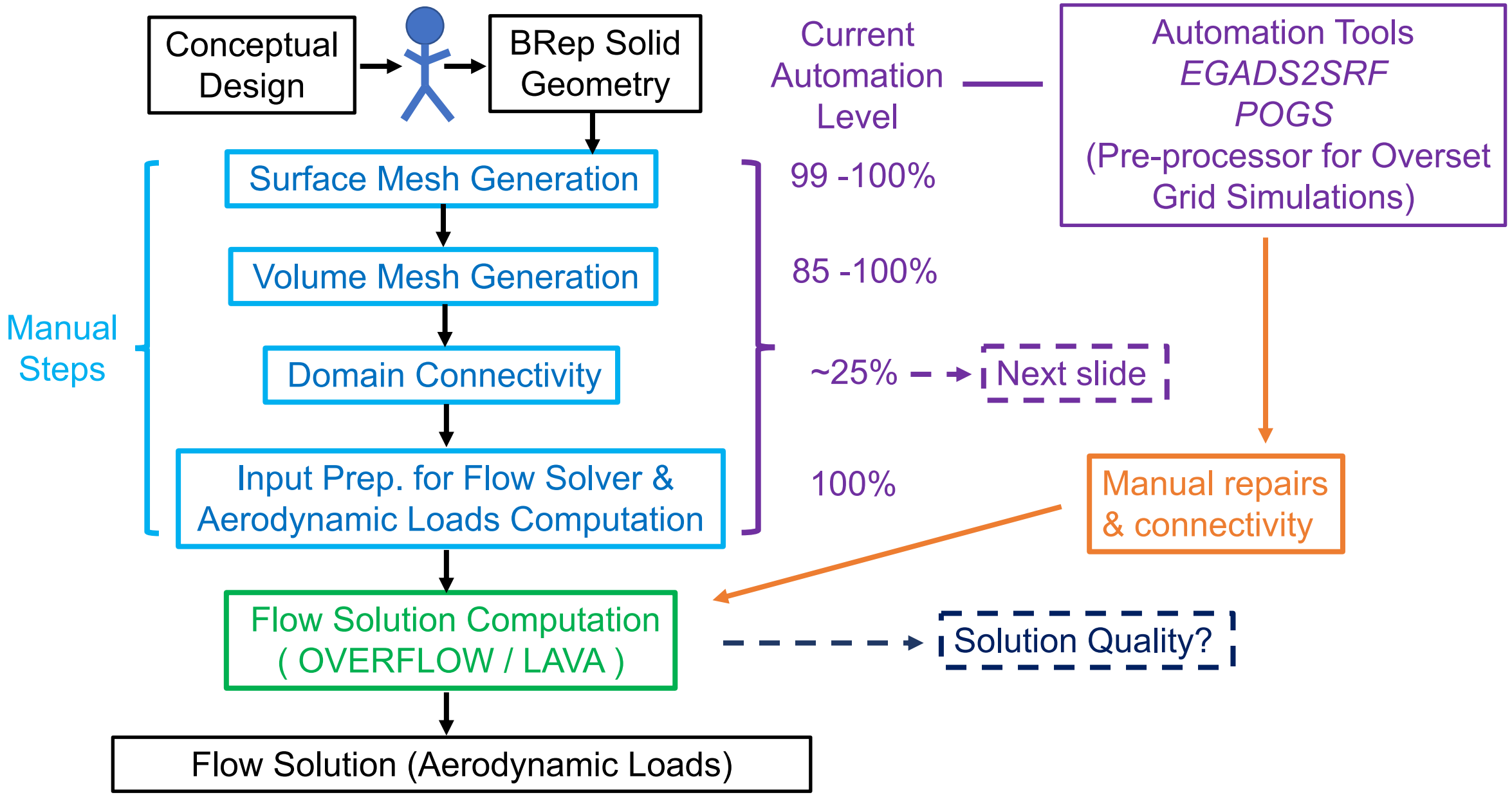


Small Ducted Propeller Test



Multi-Tiltrotor (cruise)

# OVERSET MESH GENERATION AUTOMATION SOFTWARE STATUS

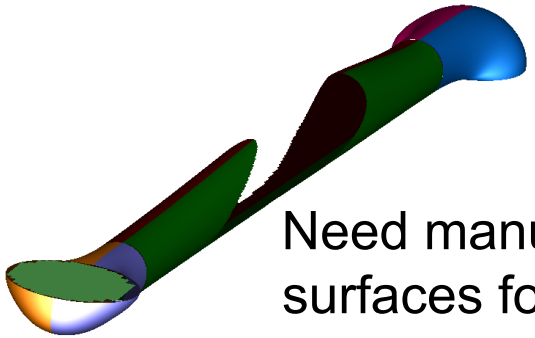


# DOMAIN CONNECTIVITY AUTOMATION STATUS

Domain Connectivity

Manual approach using OVERFLOW/DCF X-ray hole-cut

For each geometric component
1. Construction of X-ray map (50%)
2. Determination of grid list to be cut (100% 1st estimate)
3. Determination of distance offset (0%)
4. Iterations to remove orphan points (0%)



Need manual closure of component surfaces for X-ray map construction

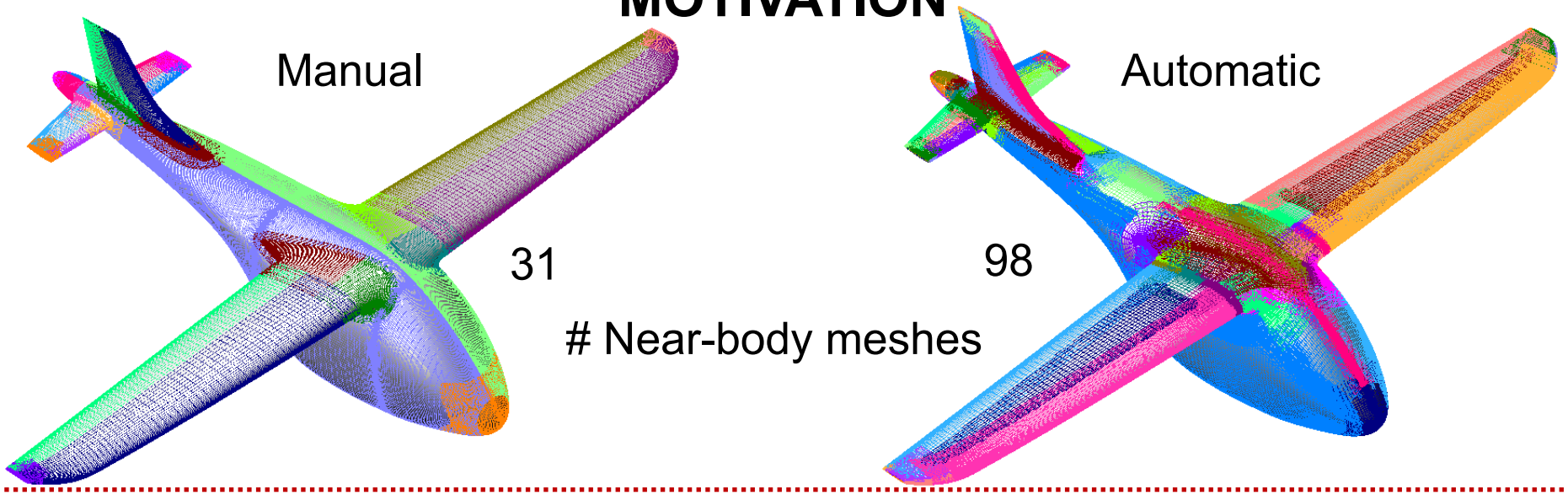
Automatic approach using distance-based hole-cuts

1. Construction of minimum hole-cut (100%)
2. Iterations of distance-based hole boundaries to remove orphan points (0%)

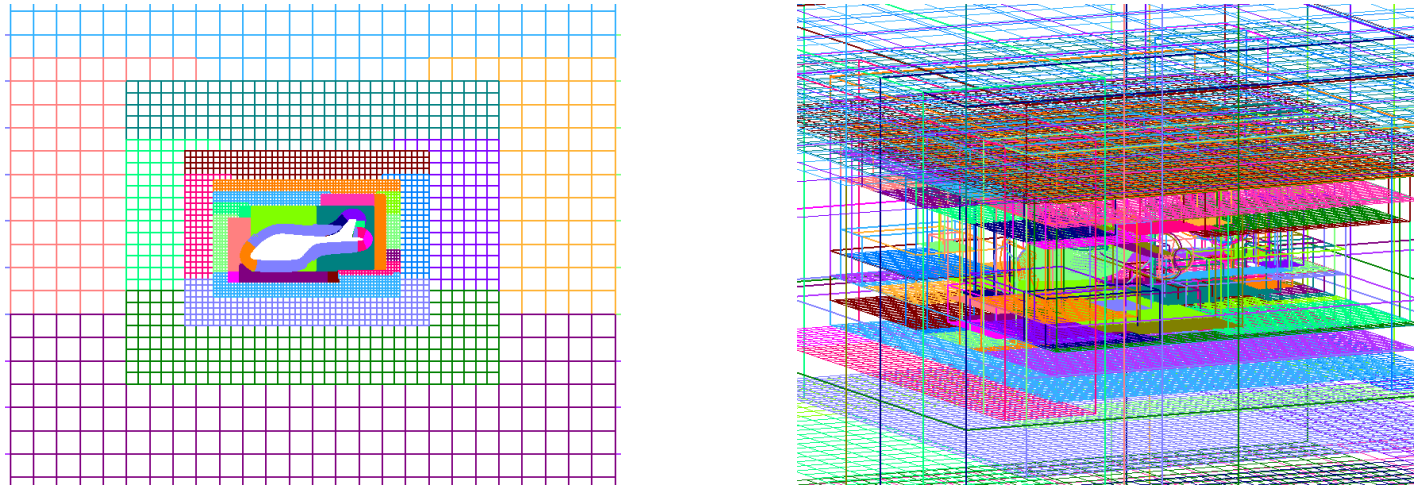
*Chan, W. M., Pandya, S. A., Advances in Distance-Based Hole Cuts on Overset Grids, AIAA Paper 2015-3425, Dallas, Texas, June, 2015.*

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# MOTIVATION




How does near-body grid fracturing affect the flow solution compared to that computed from a less fractured manually generated mesh?



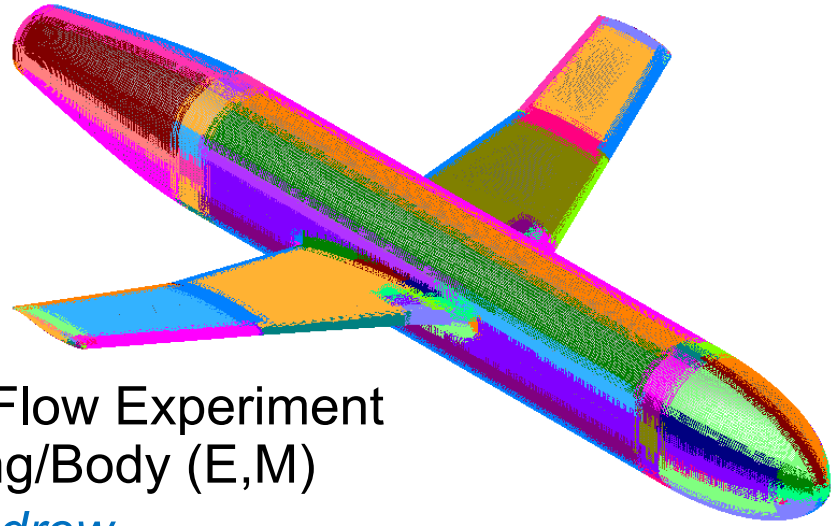
Off-body mesh treatment in OVERFLOW

# OBJECTIVES

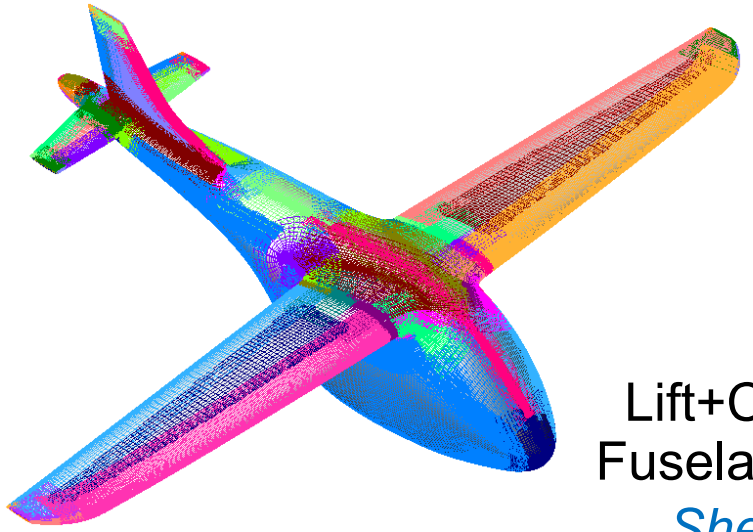
- Primary: Compare flow solutions computed on automatically and manually generated overset meshes
  - Integrated aerodynamic loads (transient, final values)
  - Convergence behavior (transient, order drop in residuals)
  - Computational cost (communication overhead, total wall clock time)
  - Parallel efficiency
- Secondary: Explore mesh refinement capability of the auto-meshing tools
  - Can a consistent mesh family be created by adjusting a small number of global parameters: max grid spacing, max dihedral angle, max stretching ratio

# APPROACH

Compare solutions on four test cases using OVERFLOW flow solver



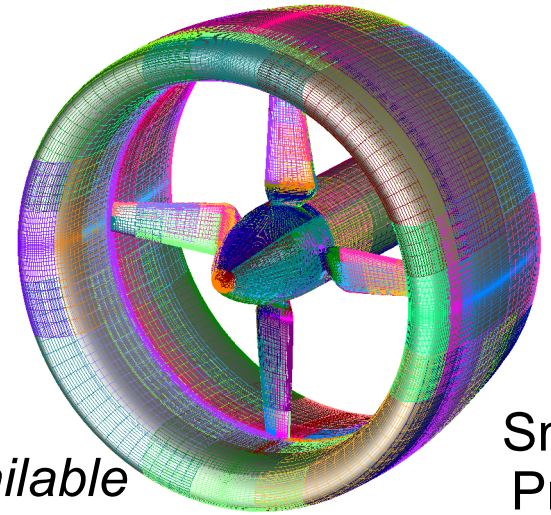
Juncture Flow Experiment
F6 Wing/Body (E,M)
*Andrew*

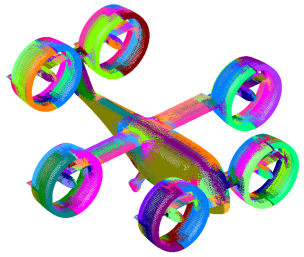


Lift+Cruise
Fuselage (M)
*Sheida*



Side-By-Side
Hybrid Fuselage
*Andrew*





Small Ducted
Propeller (E)
*James*

*E : Experimental data available*

*M: Mesh refinement study*

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# APPROACH
## NUMERICAL METHODS & CONVERGENCE CRITERIA

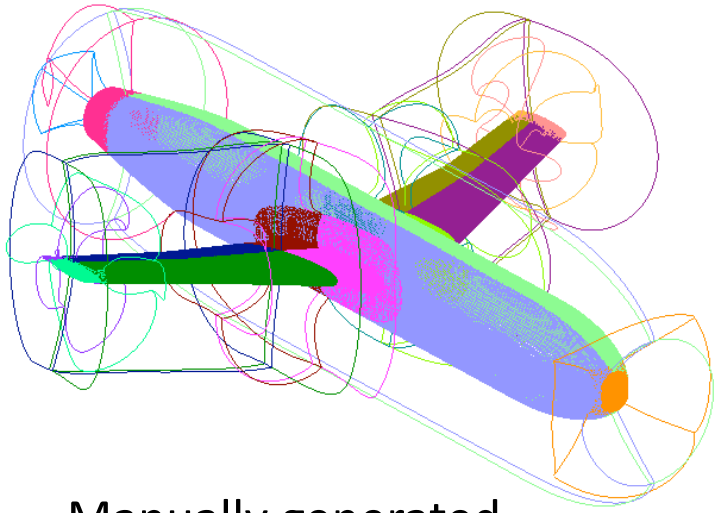
- Numerical Approach
  - OVERFLOW RANS w/ 3rd order spatial accuracy
  - Turb. Modeling:
    - SARC-QCR2013-V (Juncture Flow)
    - SARC (Lift+Cruise, Side-by-Side Hybrid, Small Ducted Propeller)
  - Unsteady Flows (Small Ducted Propeller): fast-start two-step procedure by Chaderjian* (1 deg/time-step in first 2 revs, 1/4 deg/time-step afterwards)

- Convergence Criteria
  - Steady: 5+ order residual drop; $\sigma_{C_D} < 1$ drag count or $10^{-4}$; $\sigma_{C_L}, \sigma_{C_M} < 10^{-3}$
  - Unsteady: 3+ order drop in pseudo-time residuals

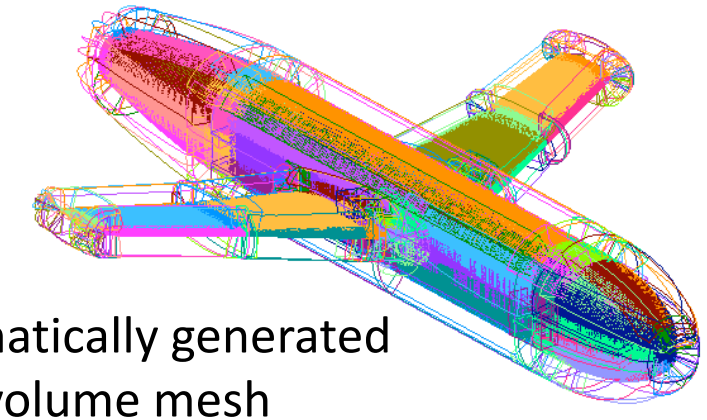
** Chaderjian, N. M., "A Quantitative Approach for the Accurate CFD Simulation of Hover in Turbulent Flow," 11th International Conference on Computational Fluid Dynamics (ICCFD11), ICCFD11-0603, July 2022.*

# JUNCTURE FLOW MODEL (JFM, F6 WING)
## MESHING TIME & EFFORT

| Flow Parameters | Value |
|---|---|
| $M_\infty$ | 0.189 |
| $\alpha$ | 5.0° |
| $Re$ | 2.4M |
| $T_\infty$ | 529° R |



Manually generated volume mesh *



Automatically generated volume mesh

| Steps | Automatic | Manual |
|---|---|---|
| Surface Meshing | 3 min (C) | 1-2 days (M) |
| Volume Meshing | 40 s (C) | 2-3 hrs (M) |
| Volume Mesh LCBC | 40 min (C) | - |
| Volume Mesh Repair | 1 hrs (M) | - |
| Domain Connectivity | 1 hrs (M) | 1 hrs (M) |
| Flow Solver Inputs | 10 min (M) | 30 min (M) |
| Total Turnaround Time | ~ 3 hrs | ~ 2 days |

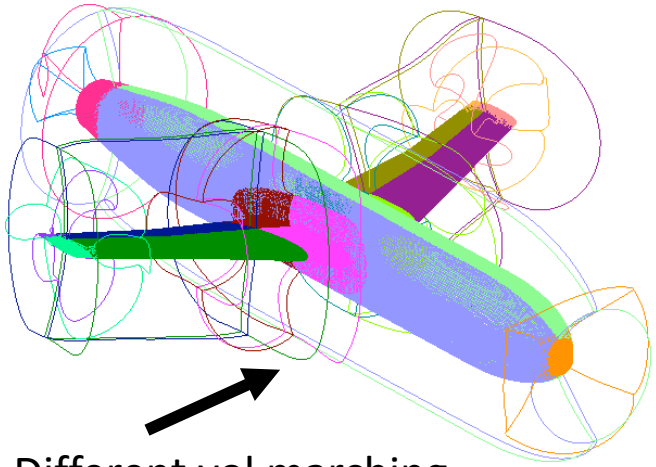
(C): CPU wall-clock time
(M): Manual labor time (assuming 8 hrs/day for an intermediate user)

* *Lee, H. C., & Pulliam, T. H., "Overflow Juncture Flow Computations Compared with Experimental Data", AIAA 2019-0080, January 2019. https://doi.org/10.2514/6.2019-0080*

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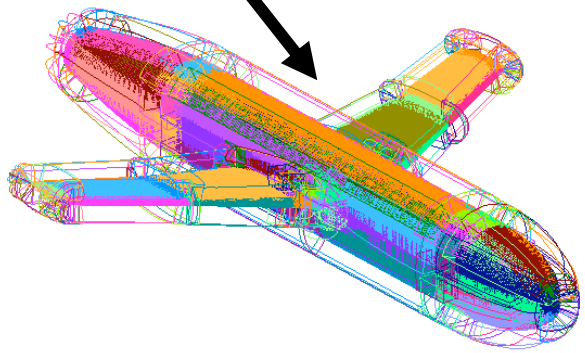
# JUNCTURE FLOW MODEL
## GRID COMPARISON

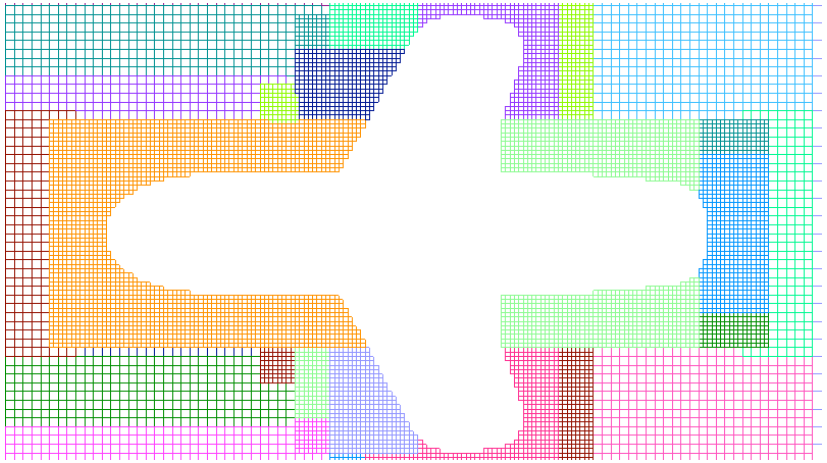
Manual

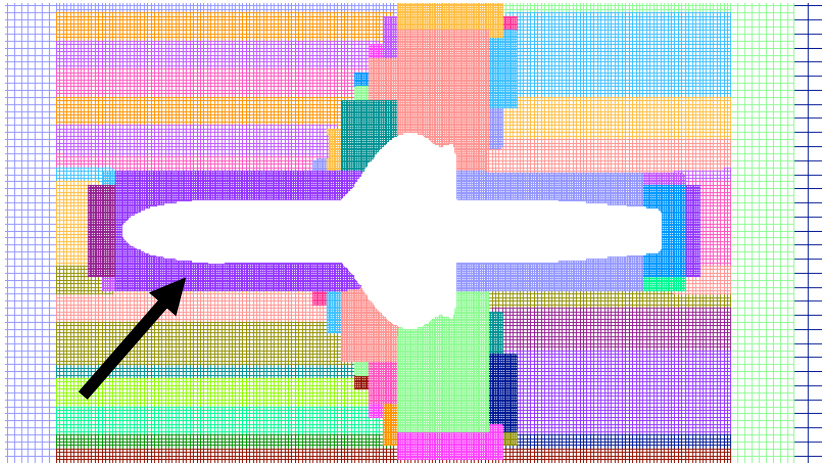


Different vol marching distances

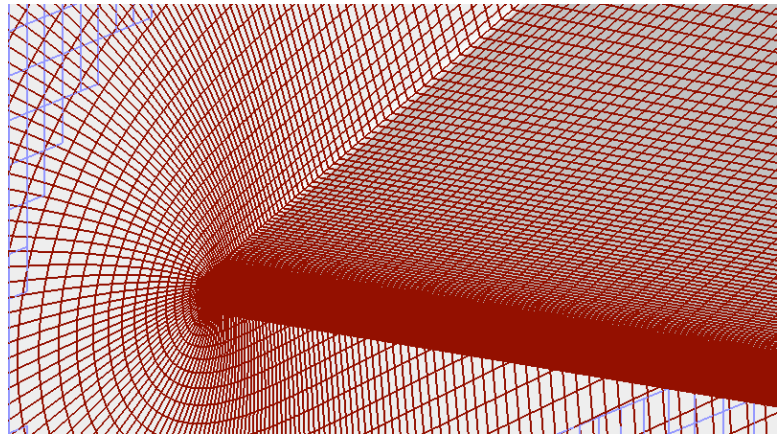
Automatic

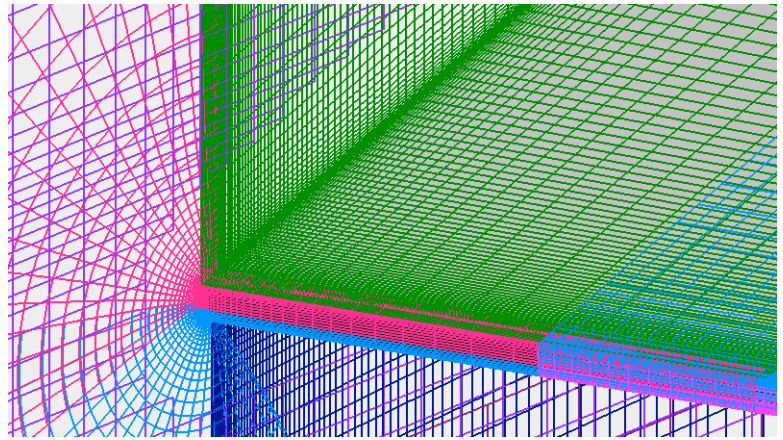






Finer off-body spacing





Near-Body

Off-Body

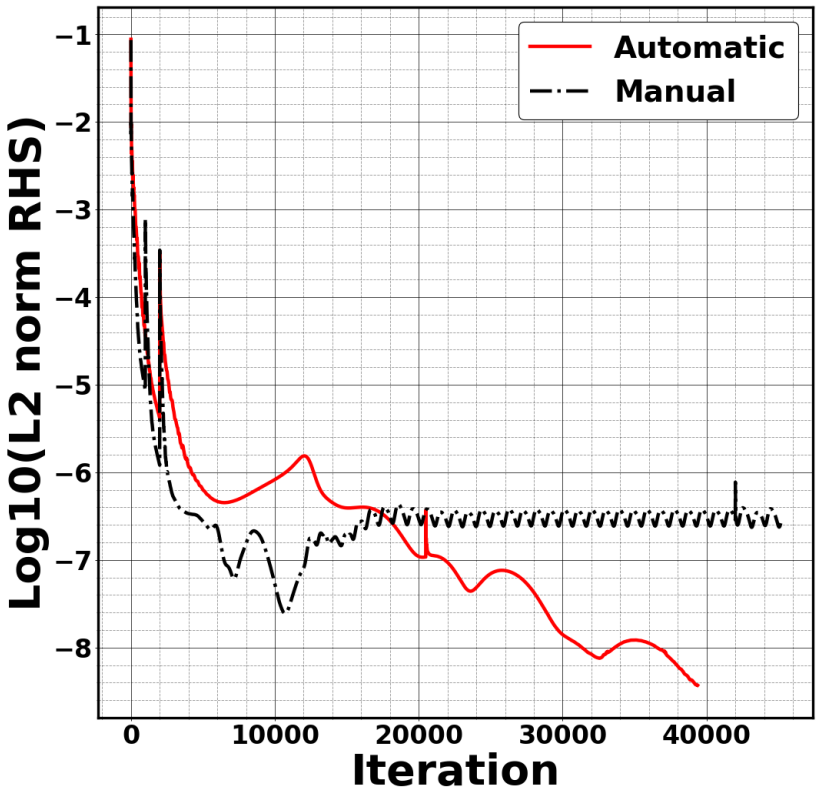
Trailing-Edge Junction

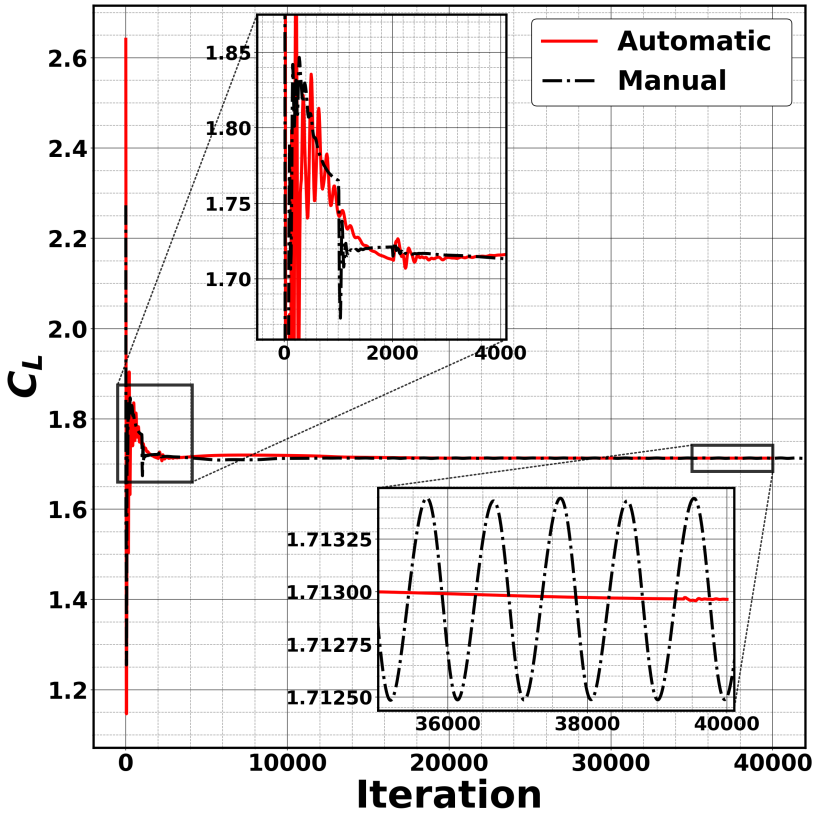
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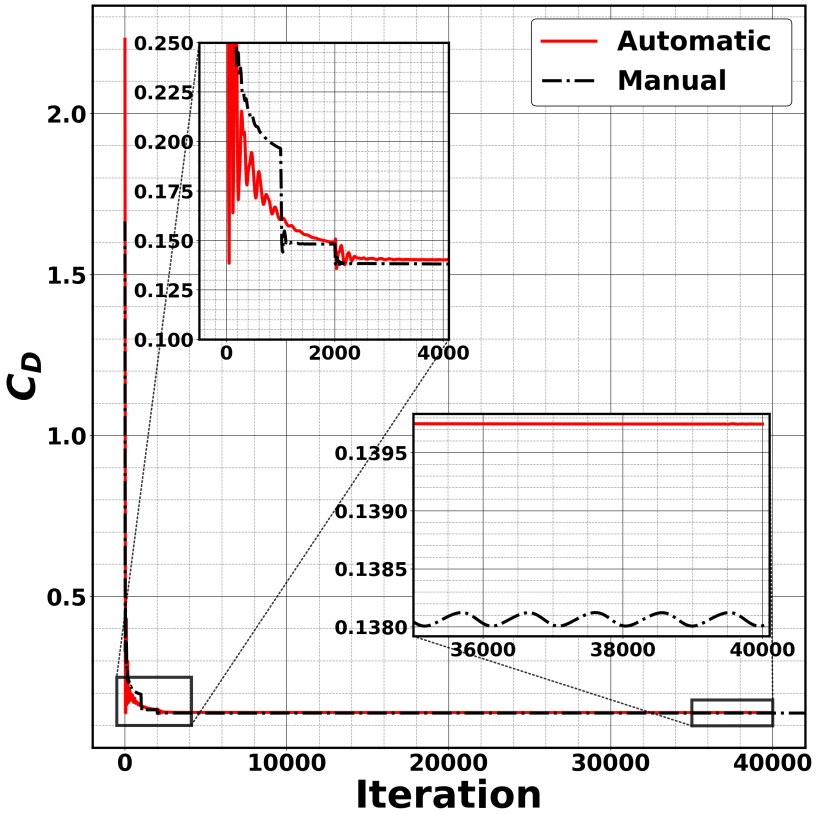
# JUNCTURE FLOW MODEL
## COMPUTATIONAL EFFICIENCY

| | | Automatic | Manual |
|---|---|---|---|
| Before MPI-Splitting | Surface Point Count | 570K | 578K |
| | # Near-Body Grids / # Total Grids | 181 / 439 | 17 / 178 |
| | Total Point Count | 45.5M | 50.9M |
| After MPI-Splitting | # Grids | 1060 | 949 |
| | Total Point Count | 52.9M | 65.2M |
| | Overset Boundary Exchange Time/Step (s) | $3.42 \times 10^{-2}$ | $3.46 \times 10^{-2}$ |
| | Parallel Efficiency | 88.8% | 92.7% |
| | Wall Time (280 Broadwell Cores, 40K steps) | 16.2 h | 21.9 h |

# JUNCTURE FLOW MODEL
## CONVERGENCE BEHAVIOR & AEROLOADS



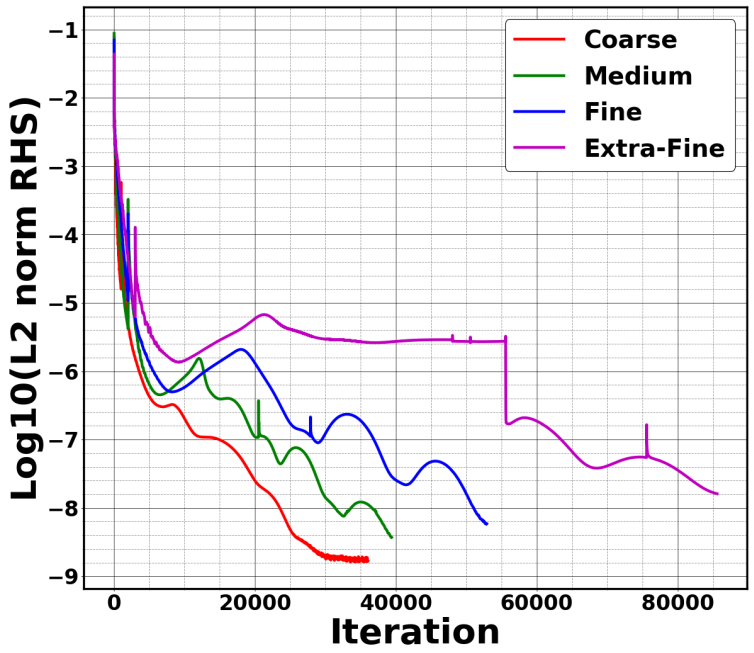



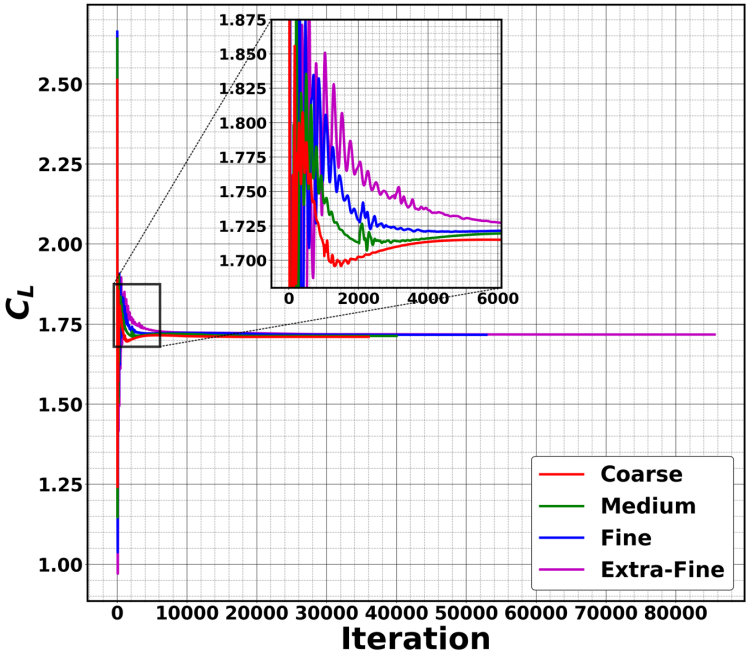

| | $C_L$ | $C_D$ | $C_M$ |
|---|---|---|---|
| Manual Mesh (avg.'d) | 1.7130 | 0.1381 | -7.6760 |
| Auto Mesh | 1.7129 | 0.1398 | -7.6739 |
| % Difference | 0.0058% | 1.23% | 0.027% |

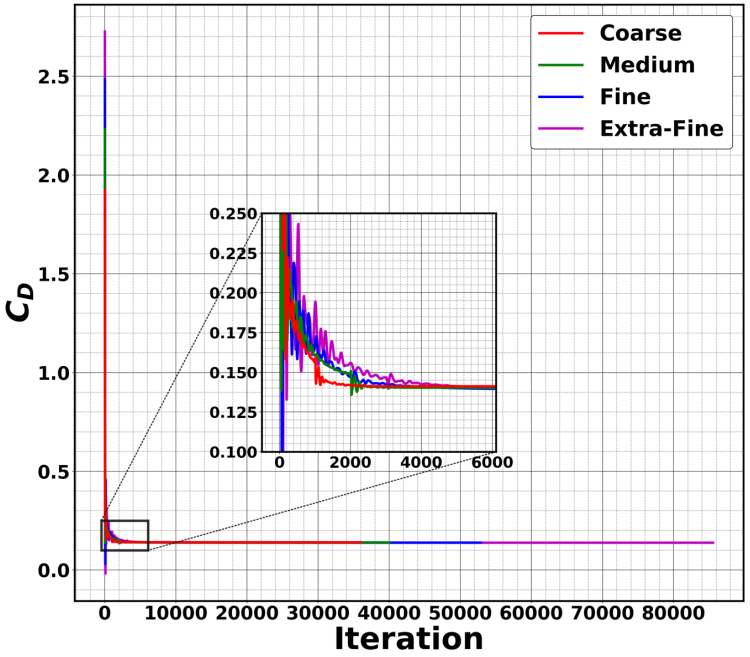
Note: Additional analyses of flow solutions for all cases can be found in manuscript

# JUNCTURE FLOW MODEL: MESH REFINEMENT
## CONVERGENCE BEHAVIOR & AEROLOADS

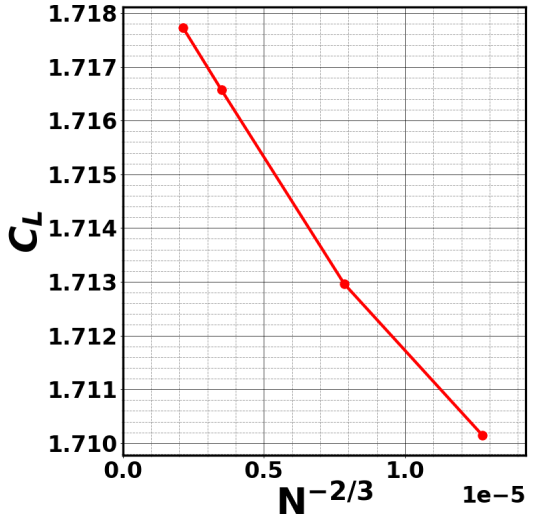
Solution Convergence

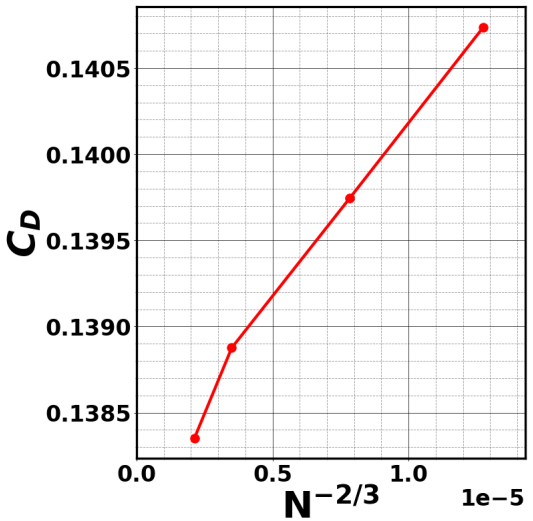


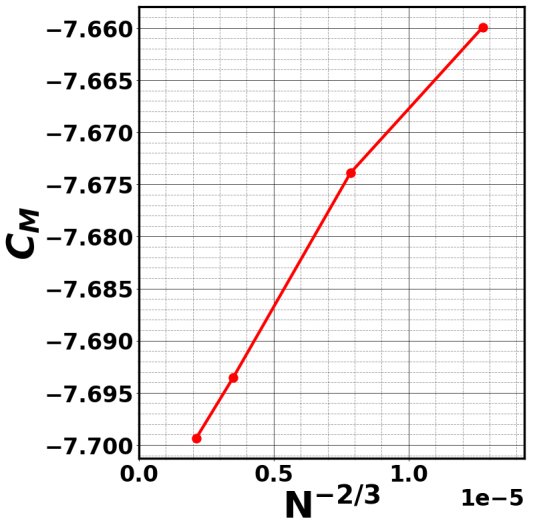




Mesh Refinement

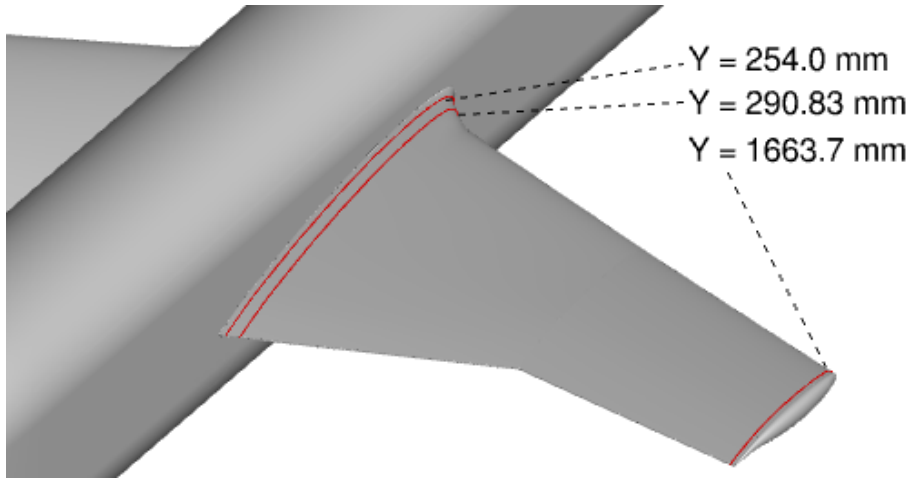


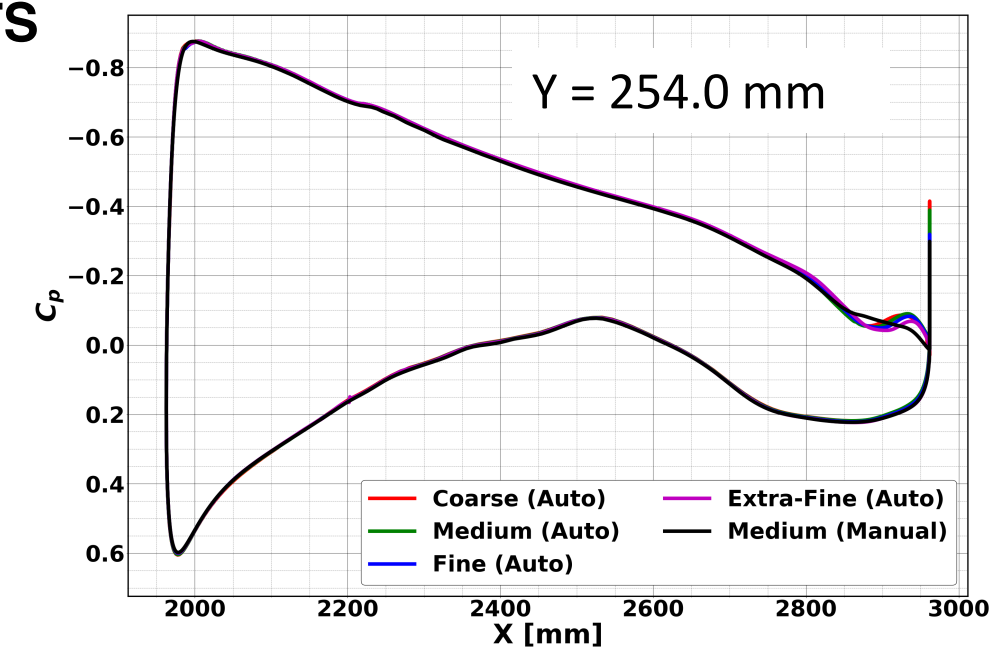



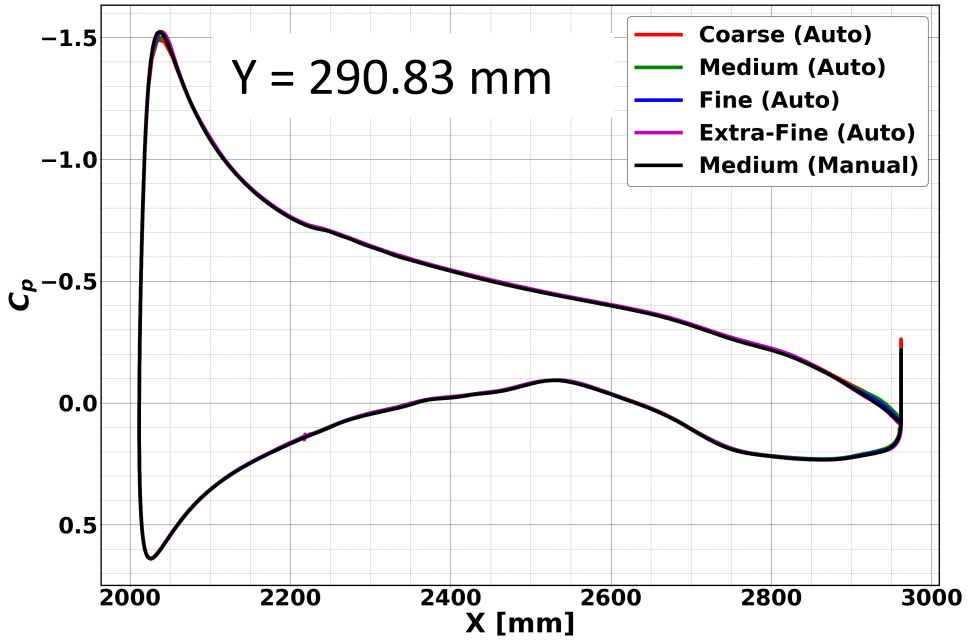



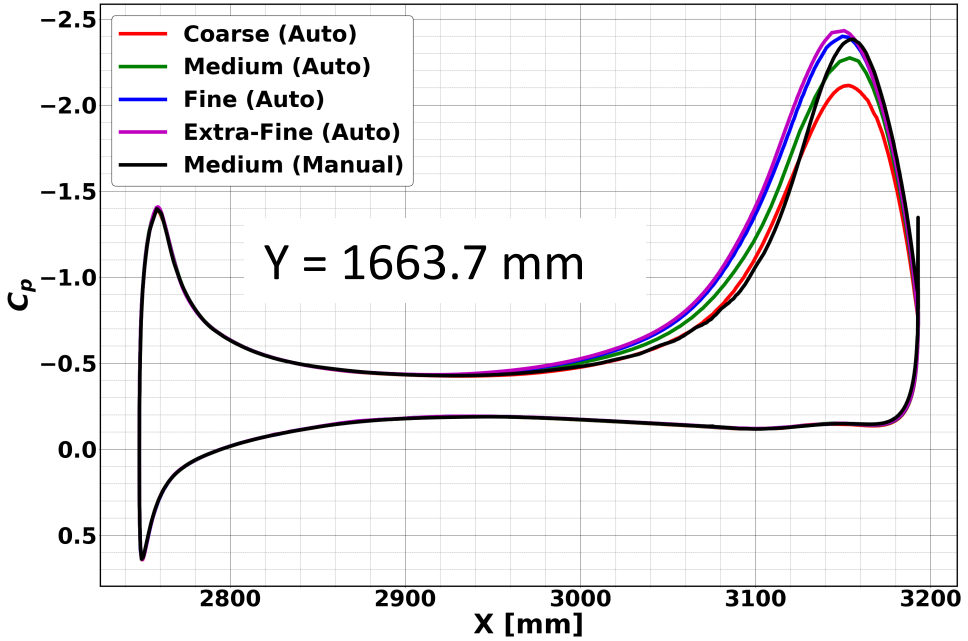
# JUNCTURE FLOW MODEL: MESH REFINEMENT

## CP CUTS



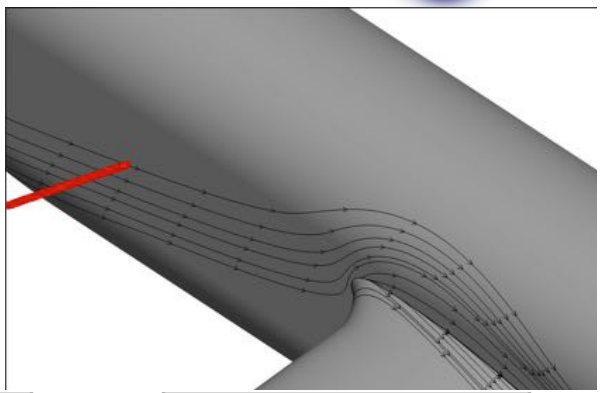



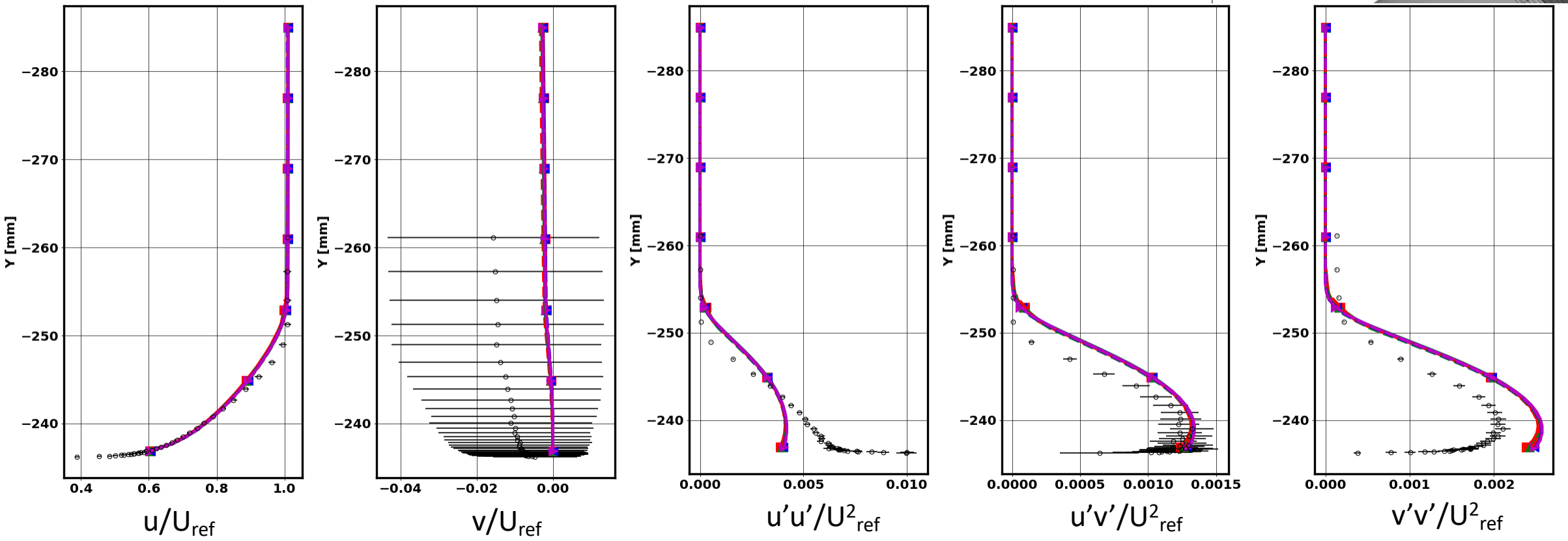
# JUNCTURE FLOW MODEL: MESH REFINEMENT

## Velocity & Shear Stress Components Line Data Profiles

Manual mesh data from Lee & Pulliam AIAA Paper 2019-0080 (dashed lines)



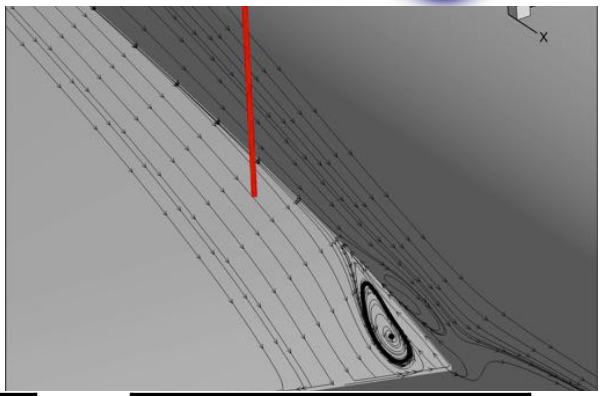
X = 1168.4 mm, Z= 0.0 mm



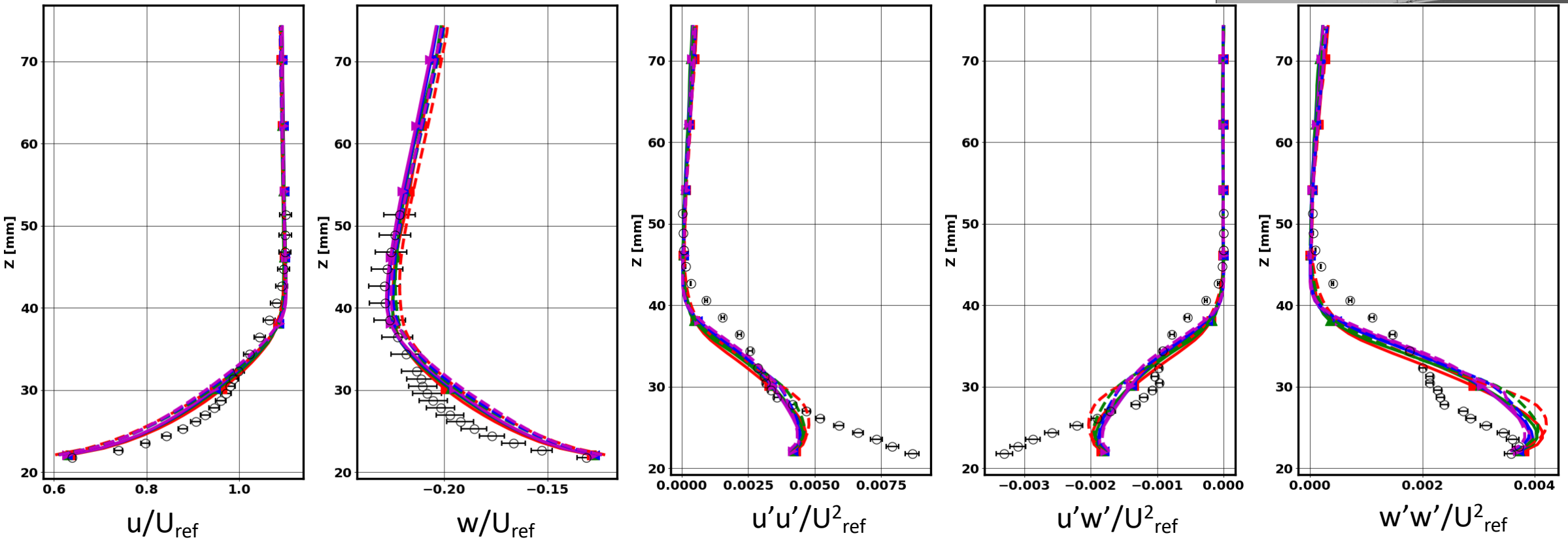
# JUNCTURE FLOW MODEL: MESH REFINEMENT

## Velocity & Shear Stress Components Line Data Profiles

Manual mesh data from Lee & Pulliam AIAA Paper 2019-0080 (dashed lines)



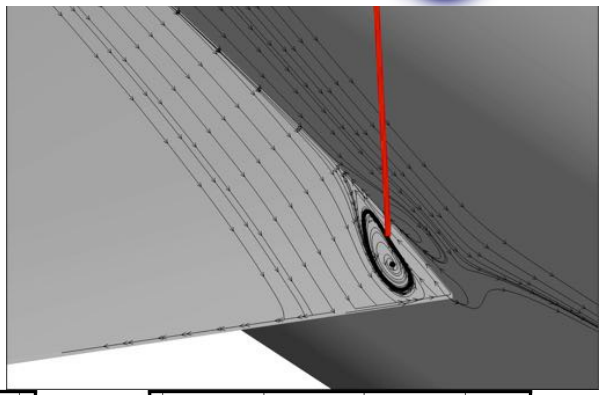
X = 2747.6 mm, Y= 266.1 mm



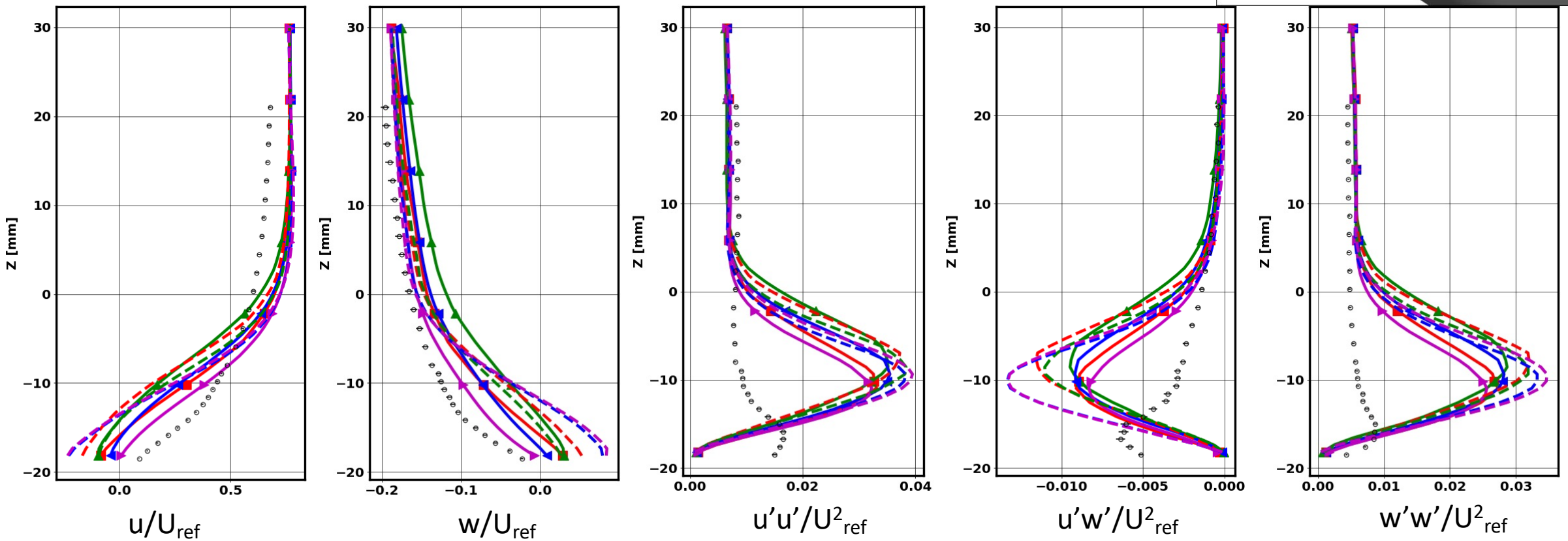
# JUNCTURE FLOW MODEL: MESH REFINEMENT

## Velocity & Shear Stress Components Line Data Profiles

Manual mesh data from Lee & Pulliam AIAA Paper 2019-0080 (dashed lines)



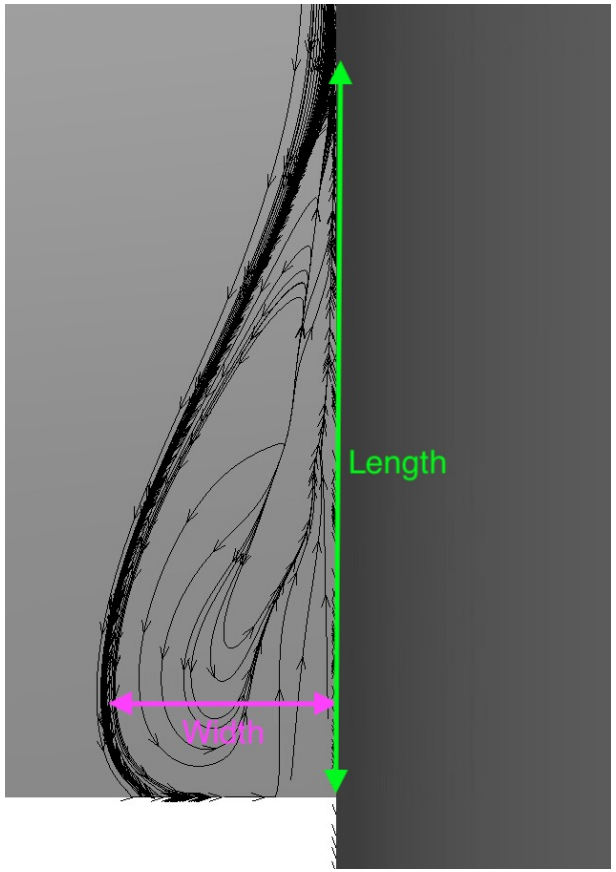
X = 2982.6 mm, Y= 246.1 mm

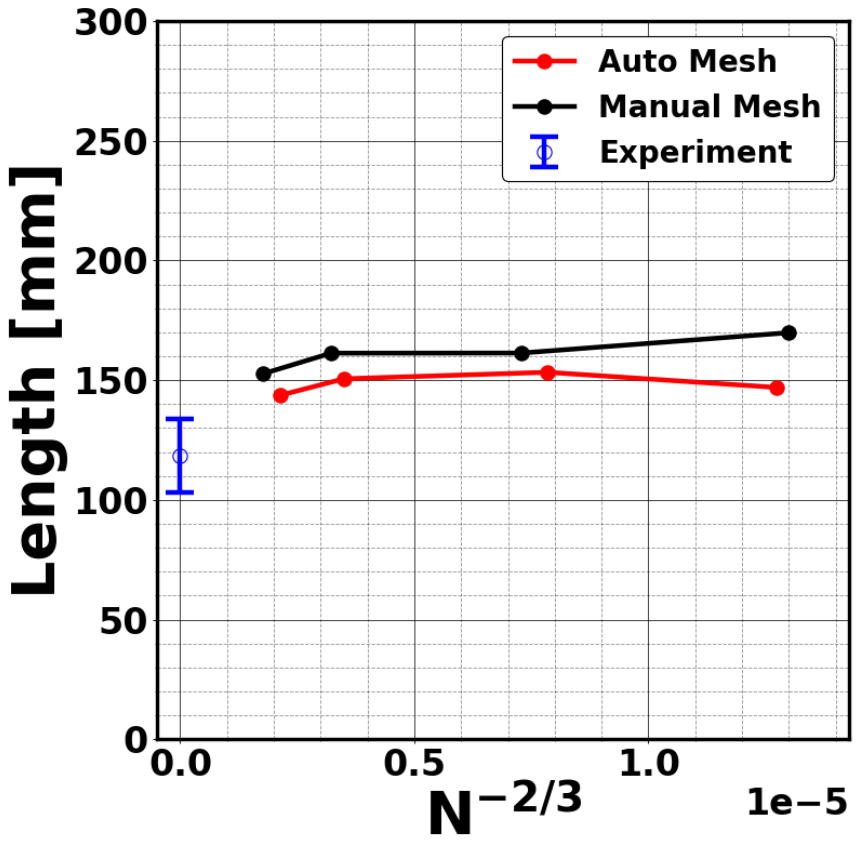


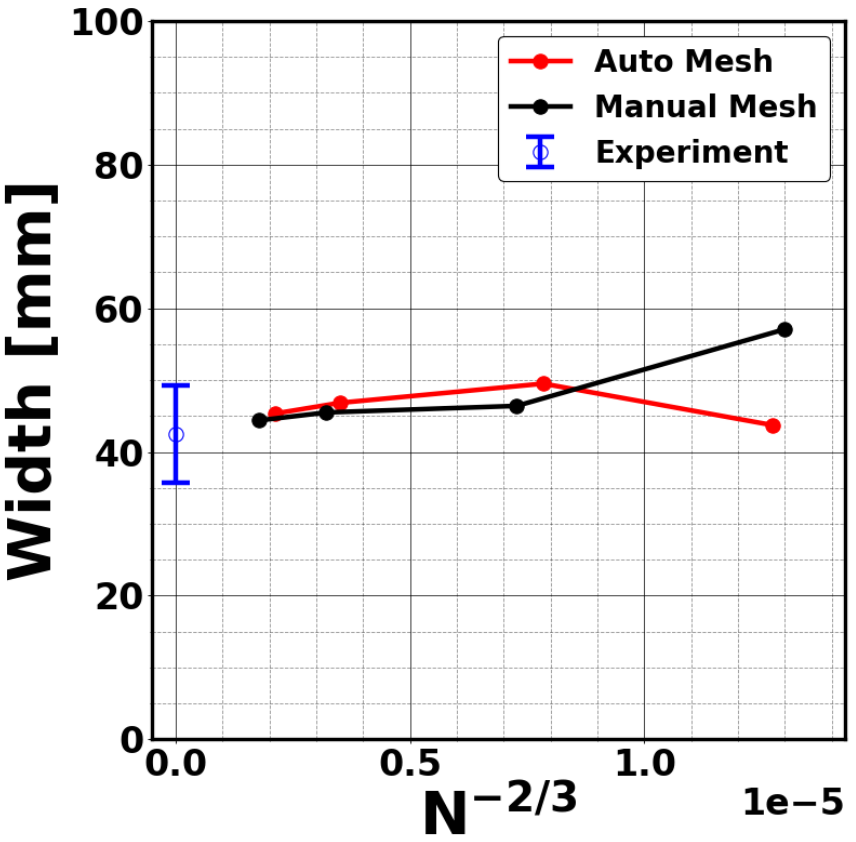
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# JUNCTURE FLOW MODEL: MESH REFINEMENT

## Separation Bubble Measurement

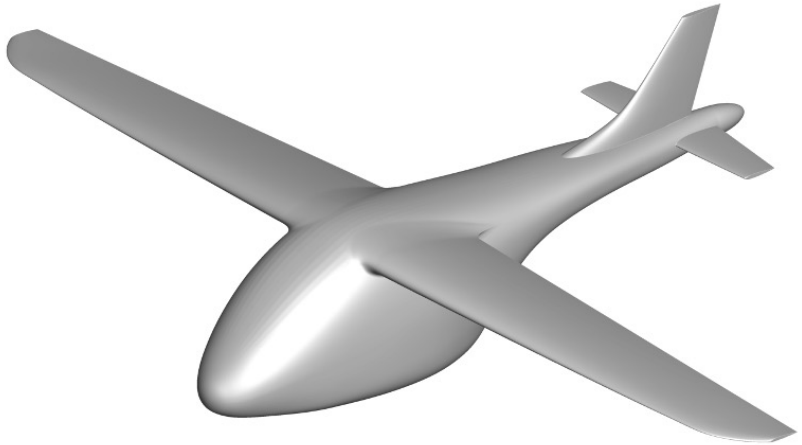


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# LIFT + CRUISE (L+C) FUSELAGE
## MESHING TIME & EFFORT

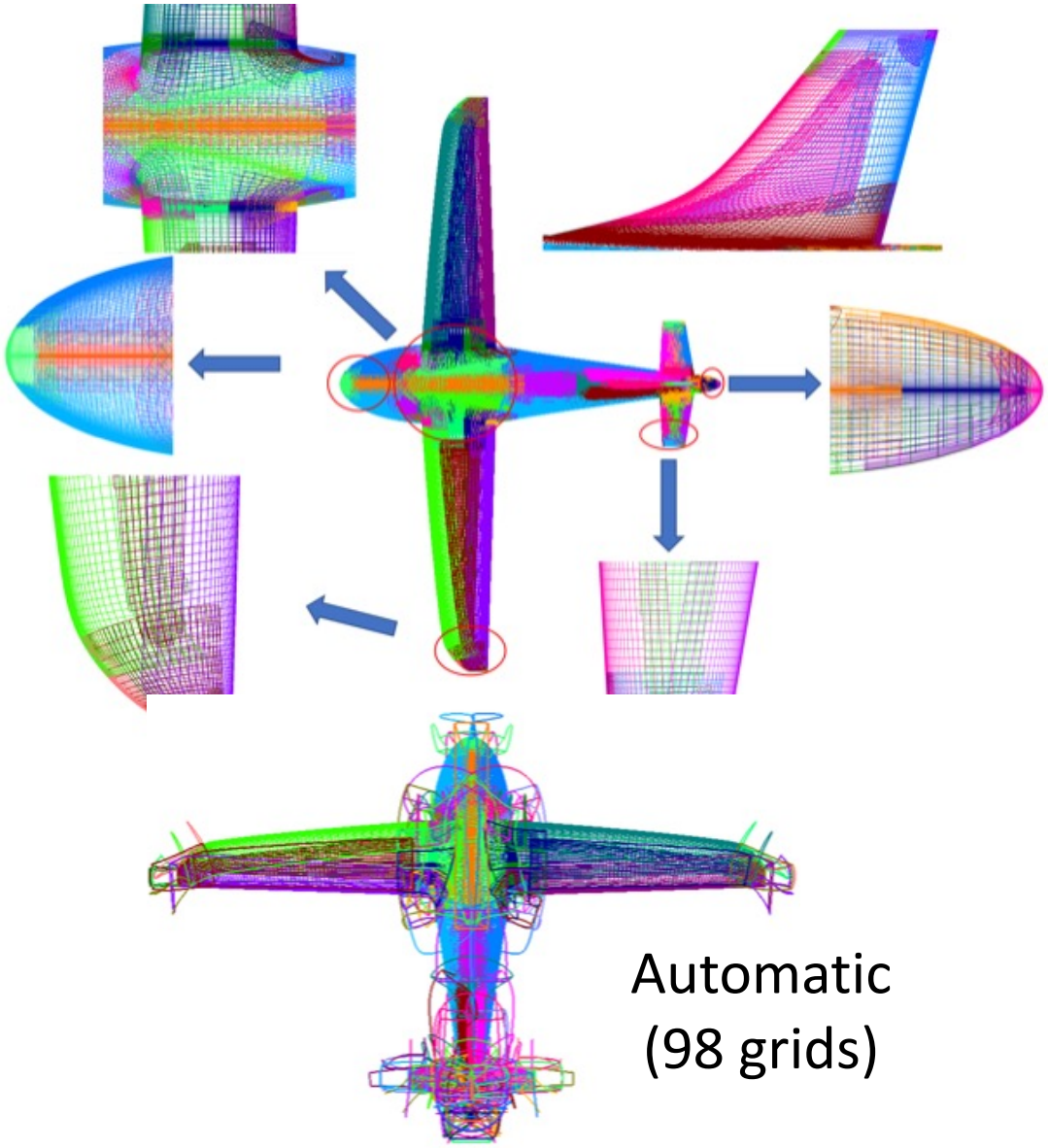


| Flow Parameters | Value [5] |
|---|---|
| $h$ | 5000 ft |
| $T_\infty$ | 500.8° R |
| $V_\infty$ | 80 kts |
| $\alpha$ | 0.0° |

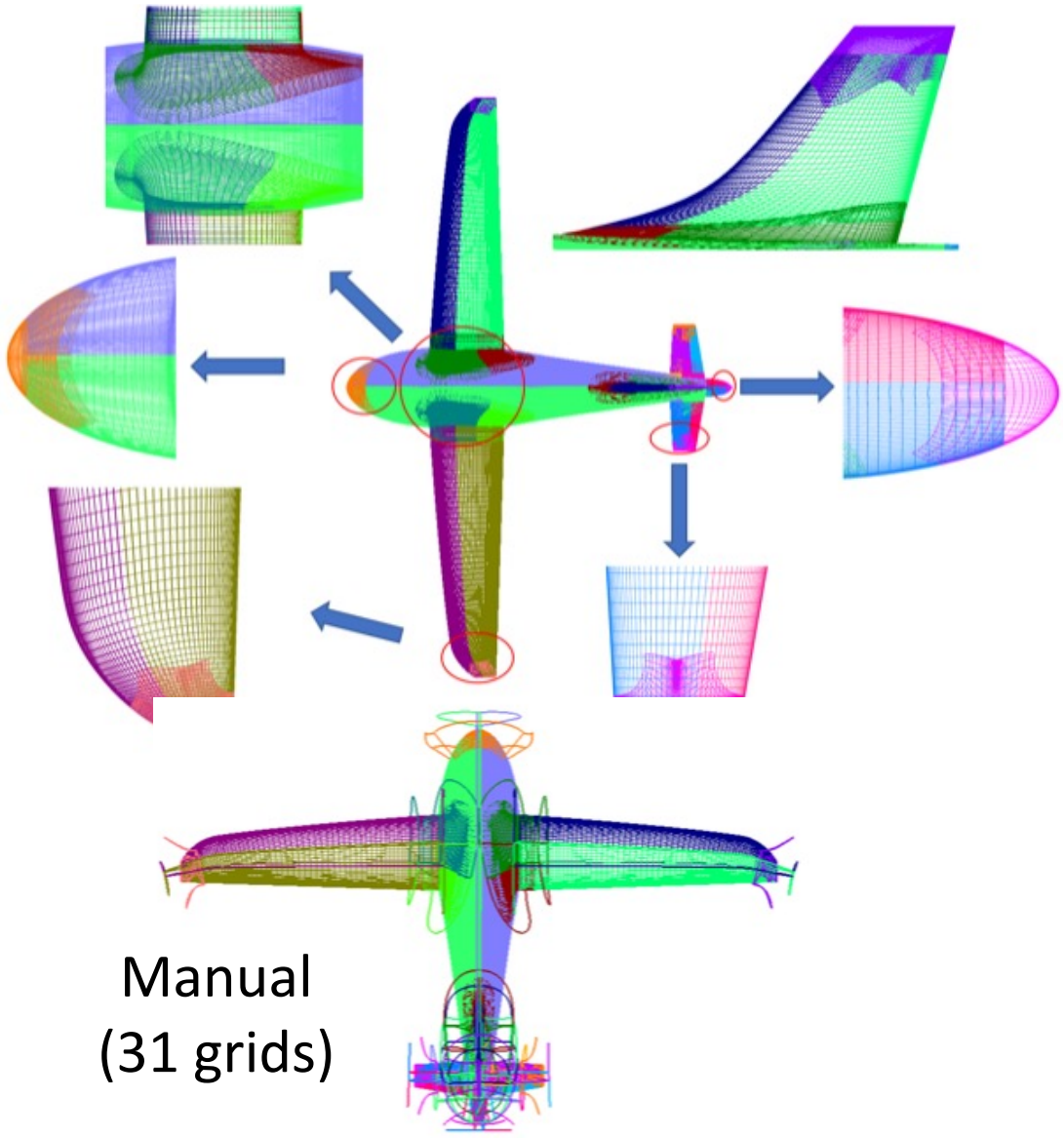
| Steps | Automatic | Manual |
|---|---|---|
| Surface Meshing | 3 min (C) | 3 wks (M) |
| Volume Meshing | 30 s (C) | 2 days (M) |
| Volume Mesh LCBC | 45 min (C) | - |
| Volume Mesh Repair | 1 day (M) | - |
| Domain Connectivity | 3 days (M) | 3 days (M) |
| Flow Solver Inputs | 10 min (M) | 1 hr (M) |
| Total Turnaround Time | ~ 4.5 days | ~ 4 wks |

(C): CPU wall-clock time
(M): Manual labor time (assuming 8hrs/day for novice user)

# LIFT + CRUISE
## GRID COMPARISON



Automatic
(98 grids)



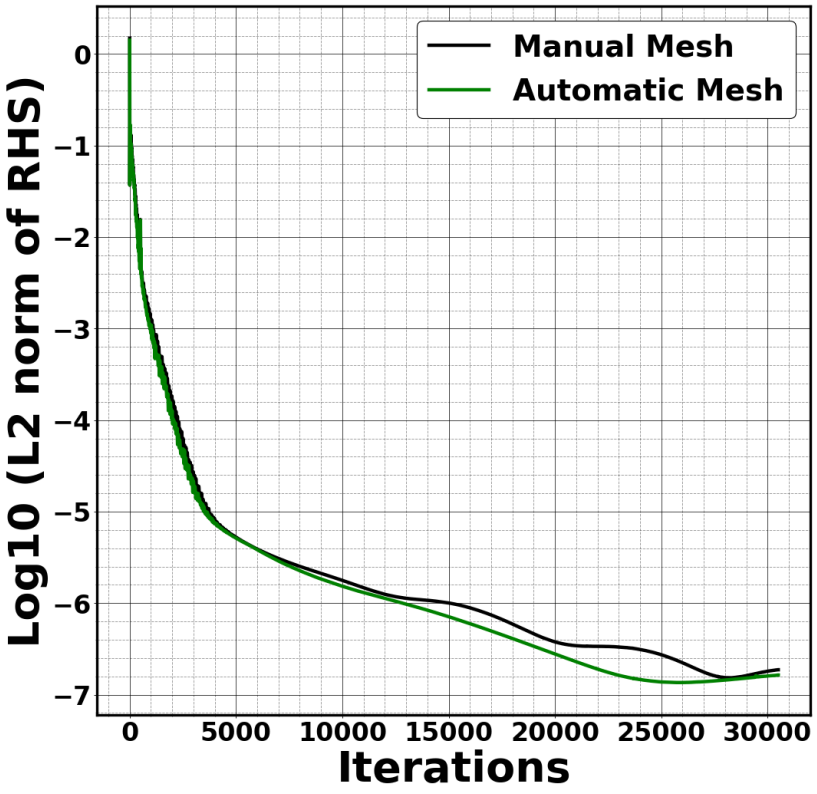
Manual
(31 grids)

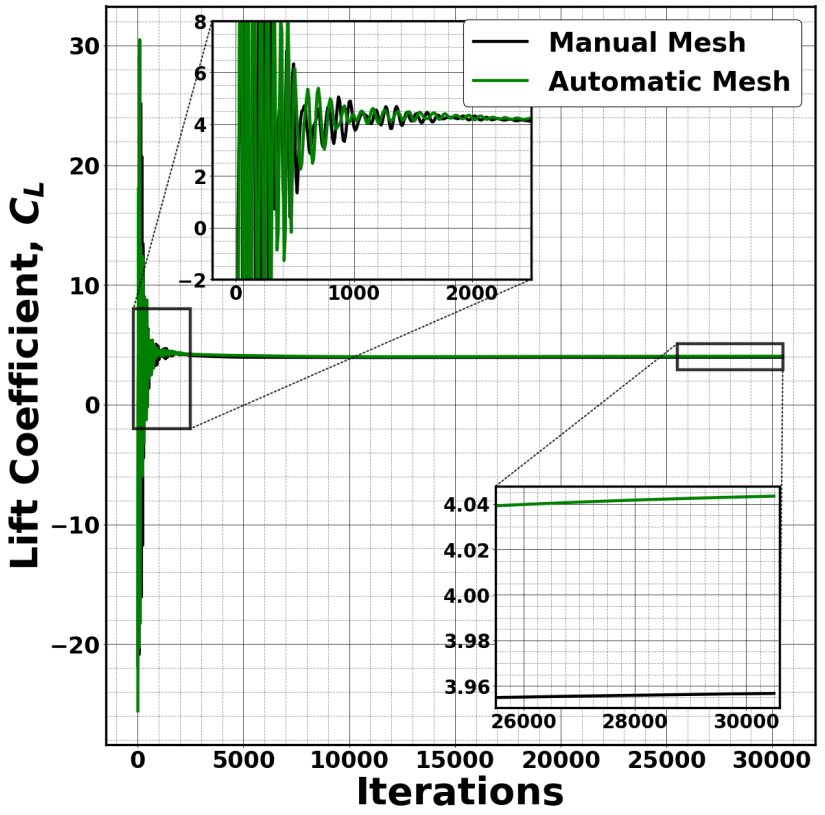
# LIFT + CRUISE
## COMPUTATIONAL EFFICIENCY

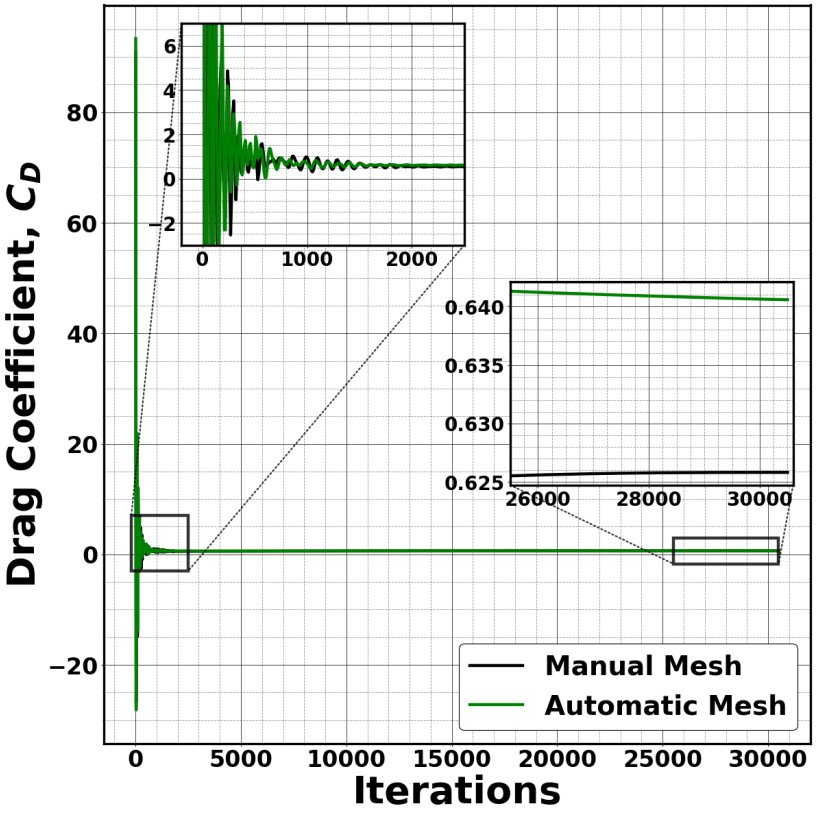
| | | Automatic | Manual |
|---|---|---|---|
| Before MPI-Splitting | # Near Body Grids / # Total Grids | 98 / 237 | 31 / 133 |
| | Fringe + Blanked Point Ct. | 3.67M | 2.62M |
| | Total Point Ct. | 13.4M | 12.3M |
| After MPI-Splitting | # Grids | 349 | 293 |
| | Total Point Ct. | 14.9M | 14.6M |
| | Overset Boundary Exchange Time/Step (s) | $2.24 \times 10^{-2}$ | $2.09 \times 10^{-2}$ |
| | Parallel Efficiency | 94.5% | 94.9% |
| | Wall Time (30K steps,72 Haswell Cores) | 9 hrs 21 min | 9 hrs 17 min |

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# LIFT + CRUISE
## CONVERGENCE BEHAVIOR & AEROLOADS



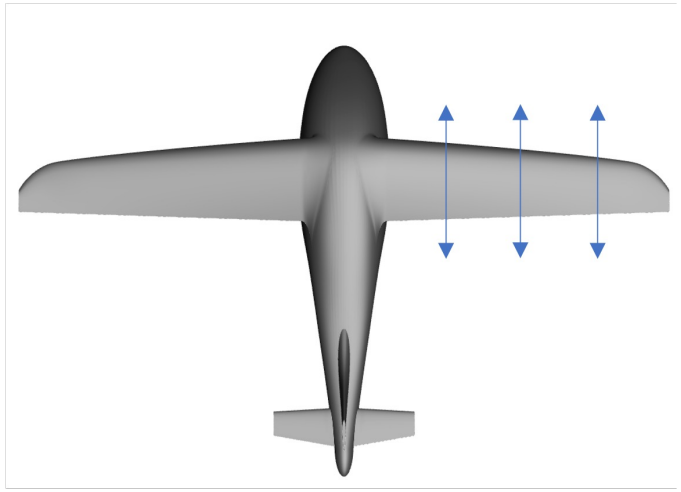



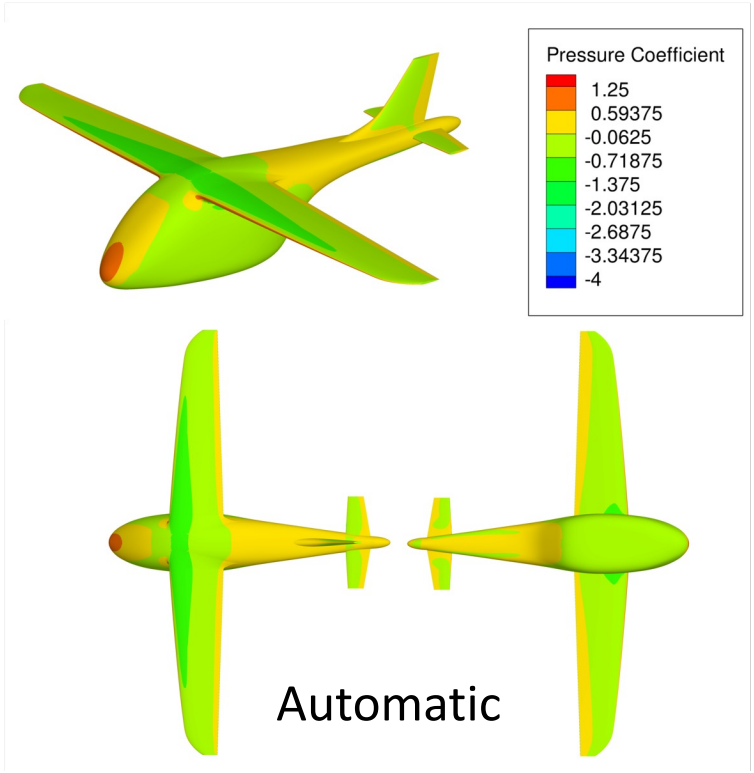

Variations fall within uncertainty from using different discretization schemes/turb. models (see paper)

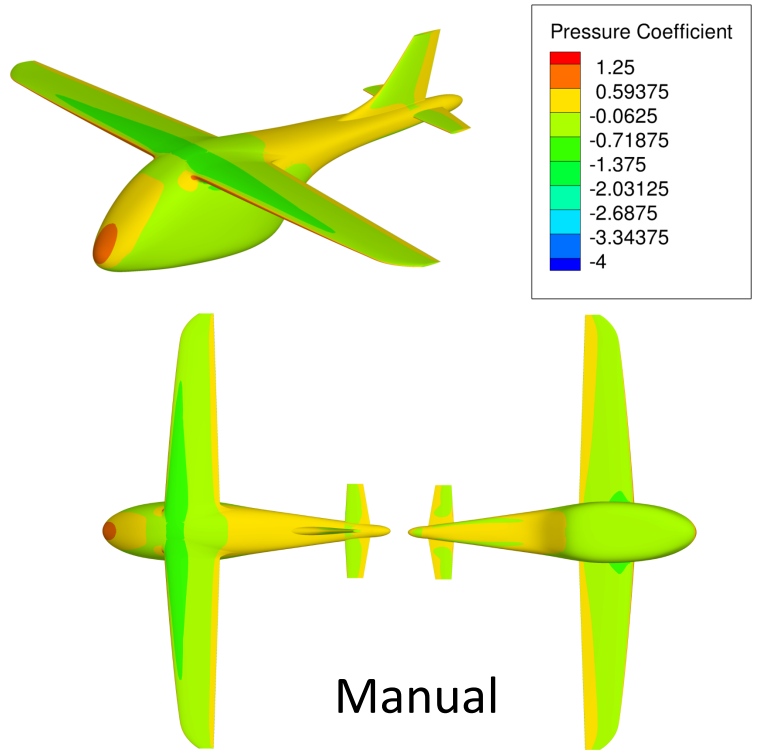
| | $C_L$ | $C_D$ | $C_M$ |
|---|---|---|---|
| Manual Mesh | 3.972 | 0.6227 | -1.311 |
| Auto Mesh | 4.043 | 0.6406 | -1.349 |
| % Difference | 1.8% | 2.8% | 2.8% |

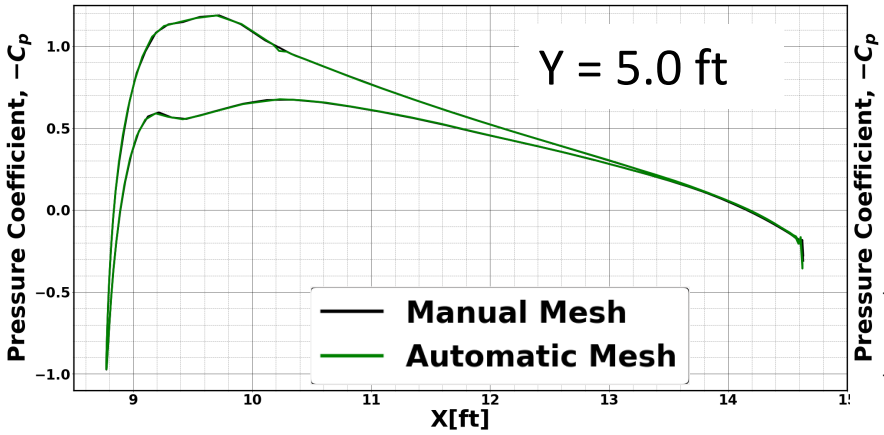
Note: $\mathbf{A_{ref}} = \mathbf{1}\ [\boldsymbol{m^2}]$

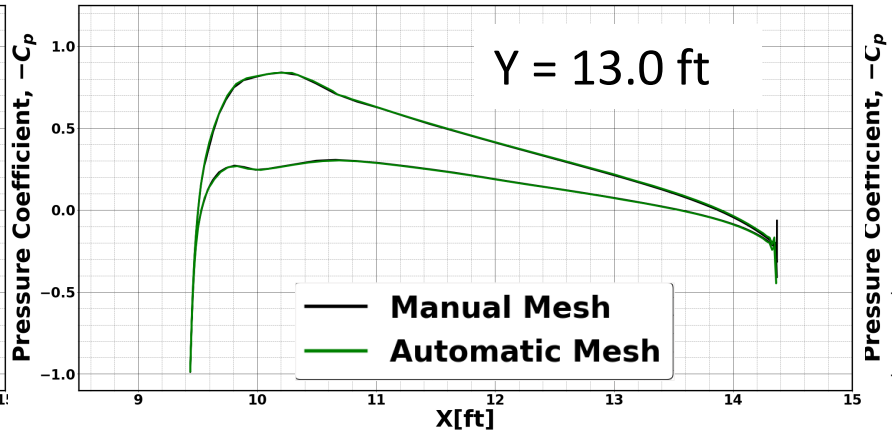
# LIFT + CRUISE
## SURFACE CP AND CP CUTS

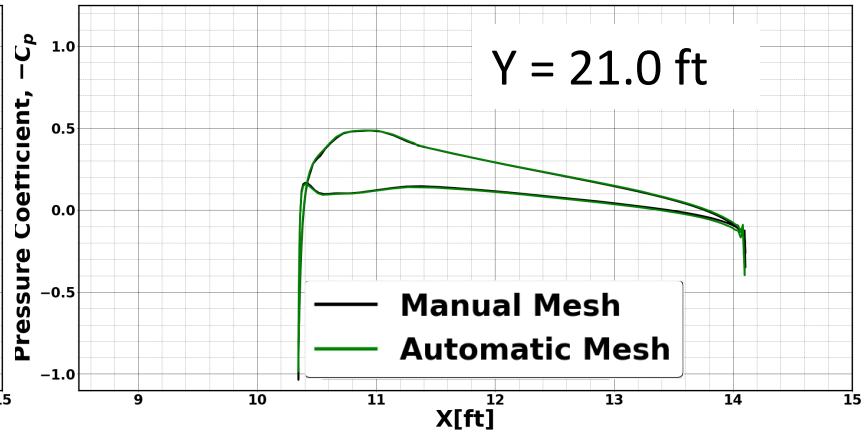




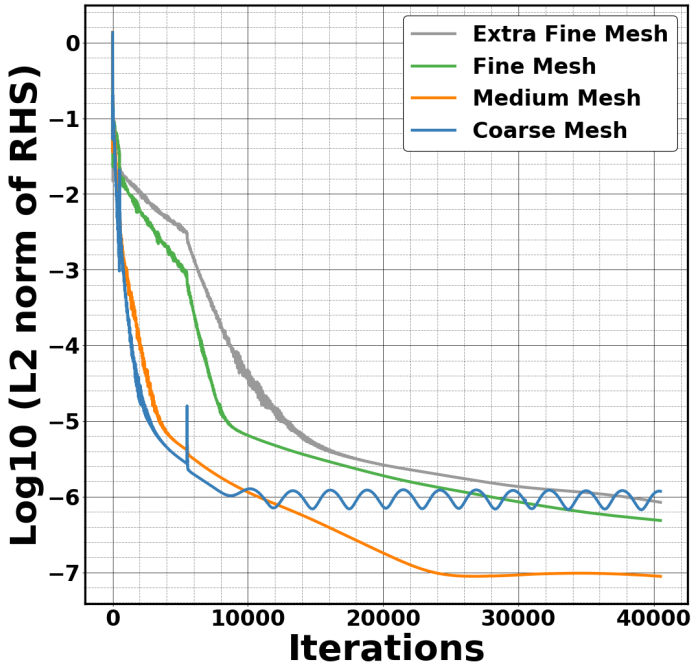



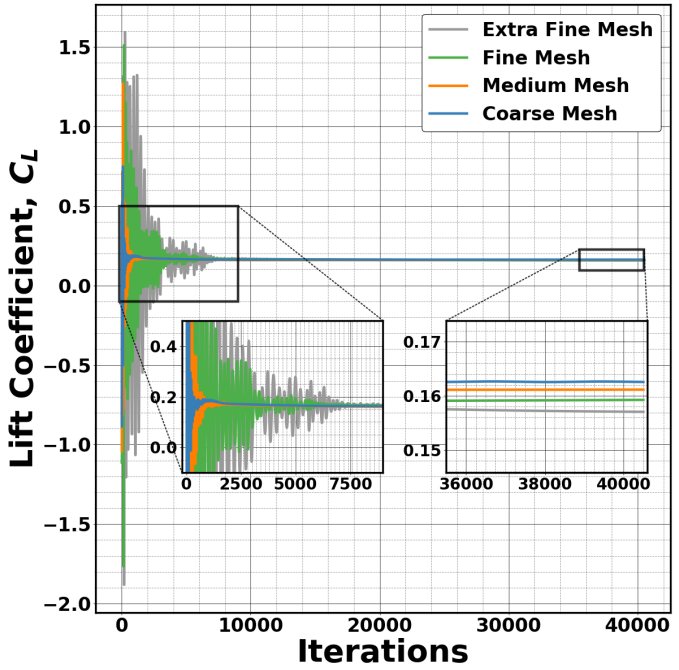



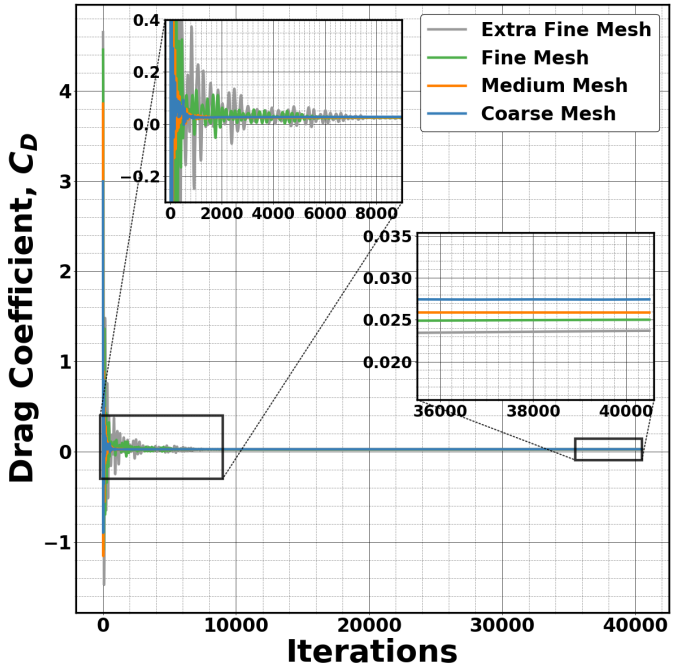



# LIFT + CRUISE: MESH REFINEMENT
## CONVERGENCE BEHAVIOR AND AEROLOADS

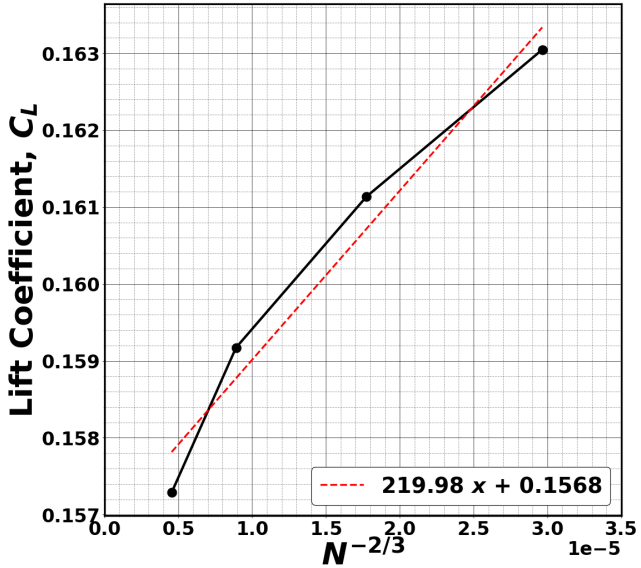
Solution Convergence

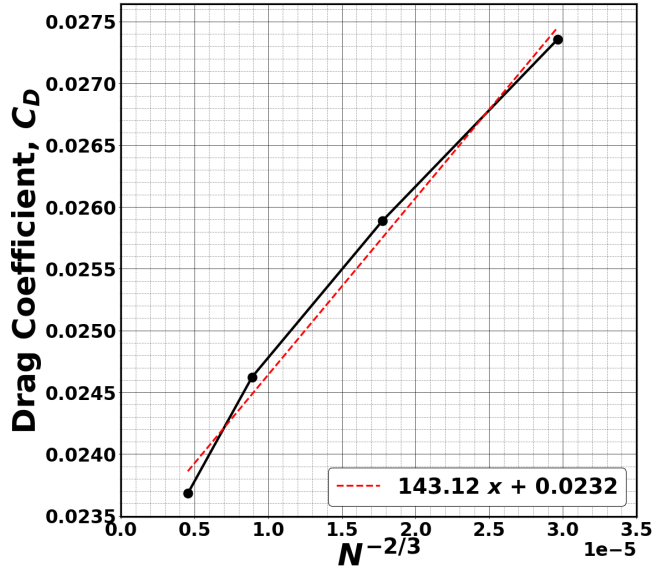


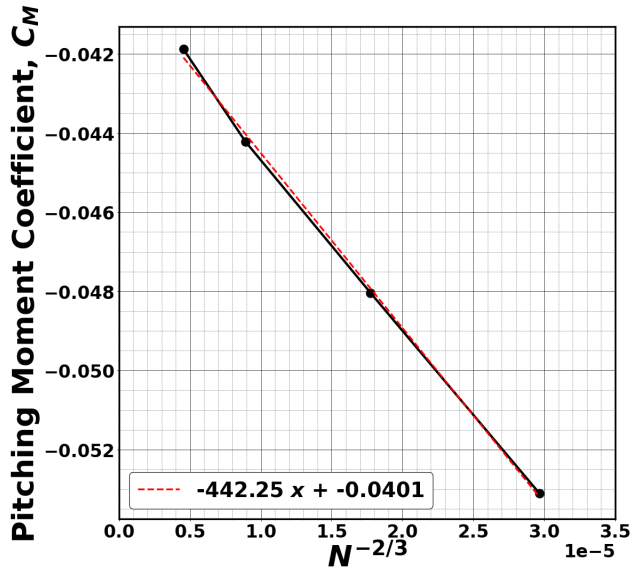




Mesh Refinement

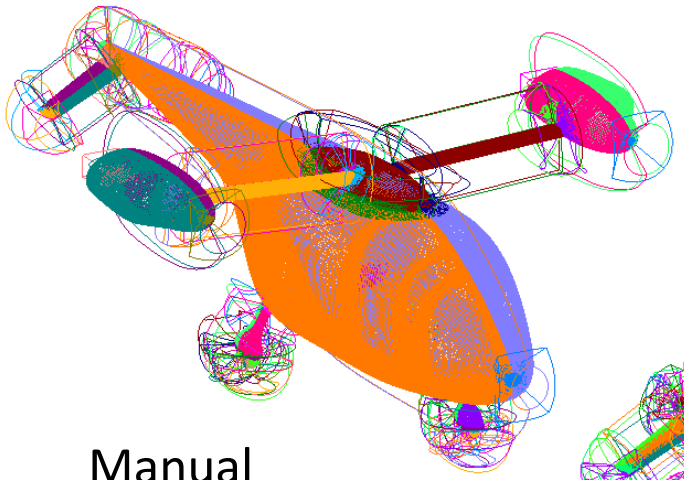


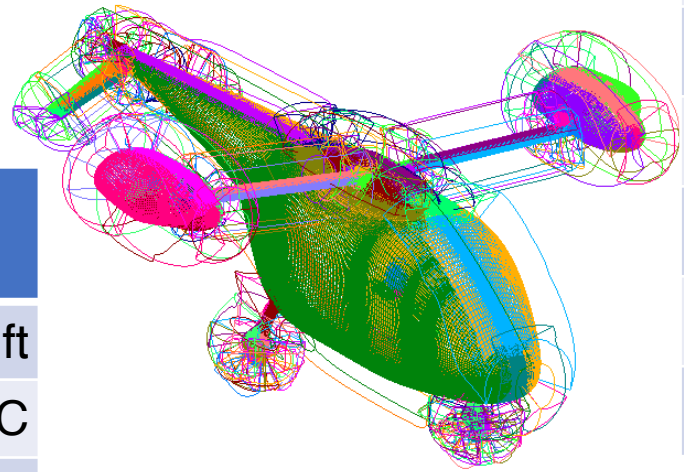



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# SIDE-BY-SIDE HYBRID FUSELAGE
## MESHING TIME/EFFORT



Manual



Automatic

| Flow Parameters | Value [6] |
|---|---|
| $h$ | 5000 ft |
| $T_\infty$ | ISA + 20° C |
| $M_\infty$ | 0.172 |
| $Re$ | 1.9 x $10^6$ |
| $\alpha$ | 0.0° |

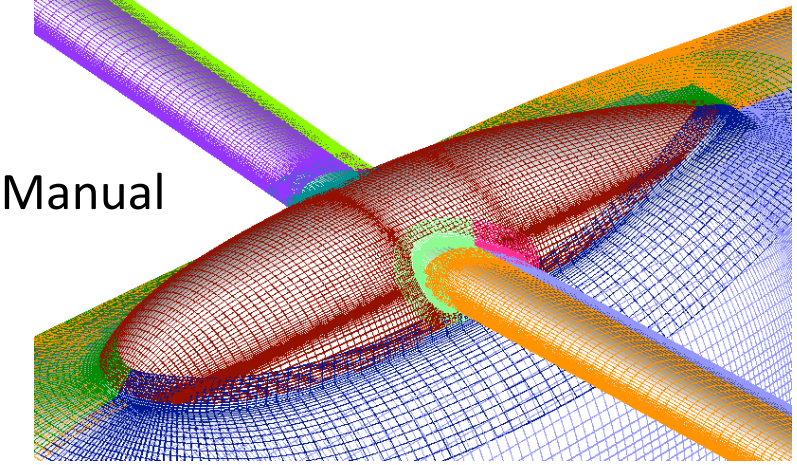
| Steps | Automatic | Manual |
|---|---|---|
| Surface Meshing | 4 min (C) | 2-3 wks (M) |
| Volume Meshing | 12 s (C) | 1 day (M) |
| Volume Mesh LCBC | 1.5 hrs (C) | - |
| Volume Mesh Repair | 4 hrs (M) | - |
| Domain Connectivity | 4 hrs (M) | 2 hrs (M) |
| Flow Solver Inputs | 10 min (M) | 30 min (M) |
| Total Turnaround Time | ~ 1 day | ~ 2-3 wks |

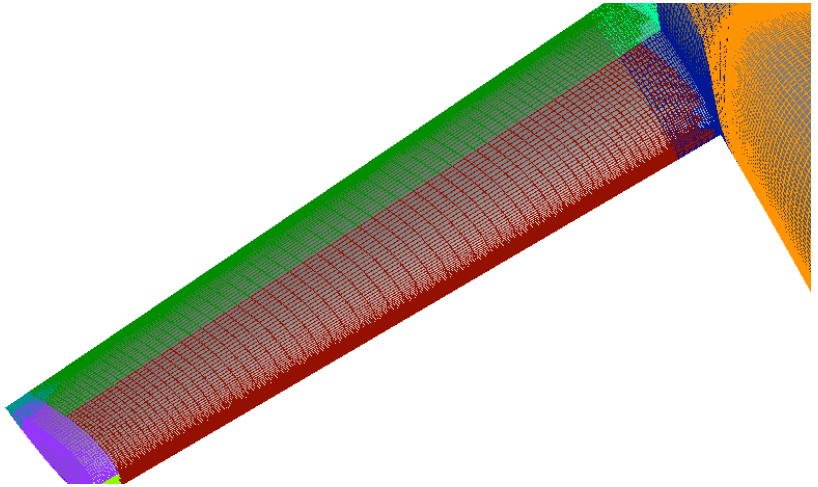
(C): CPU wall-clock time
(M): Manual labor time (assuming 8 hrs/day for a intermediate user)

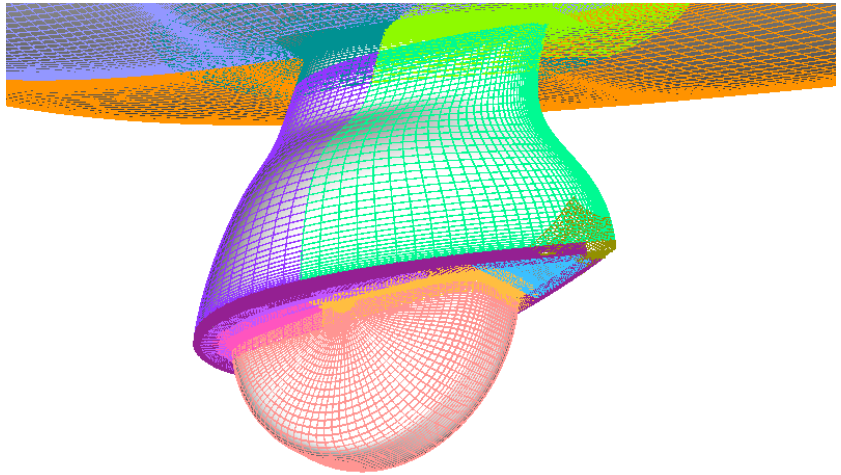
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# SIDE-BY-SIDE
## GRID COMPARISON

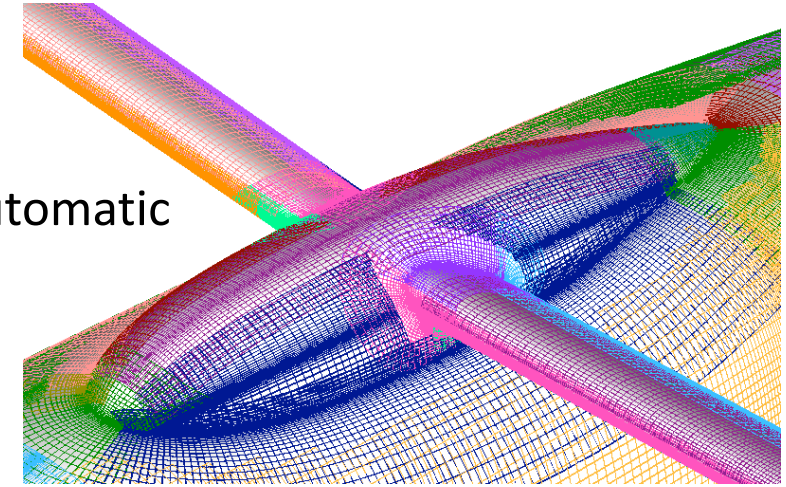
Manual

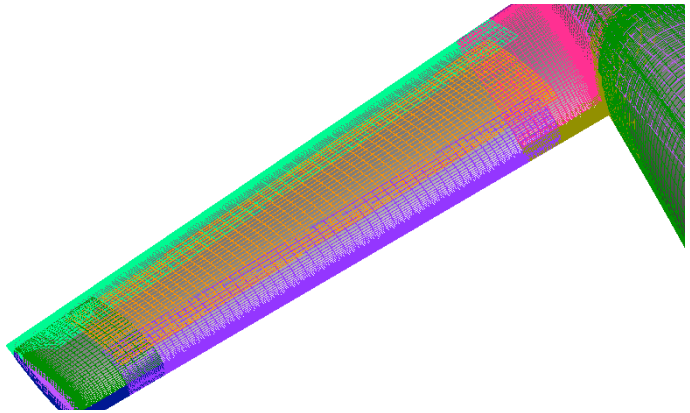


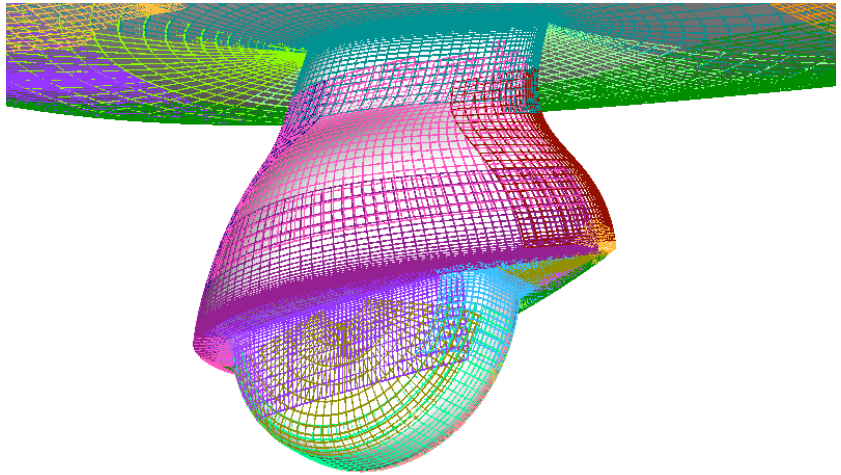




Automatic







SBS Center Pod

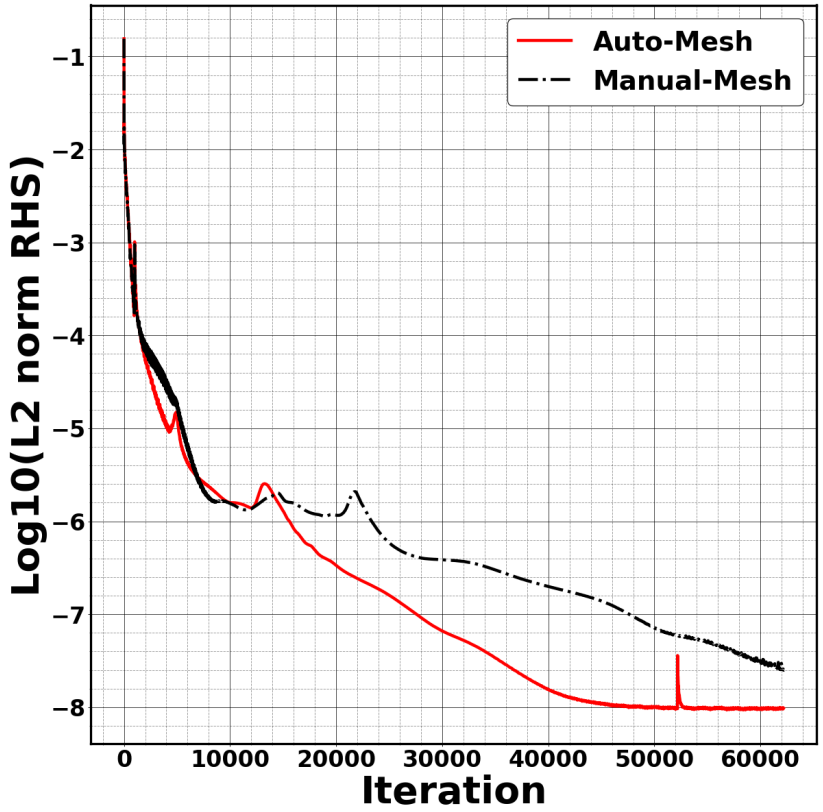
Right Tail

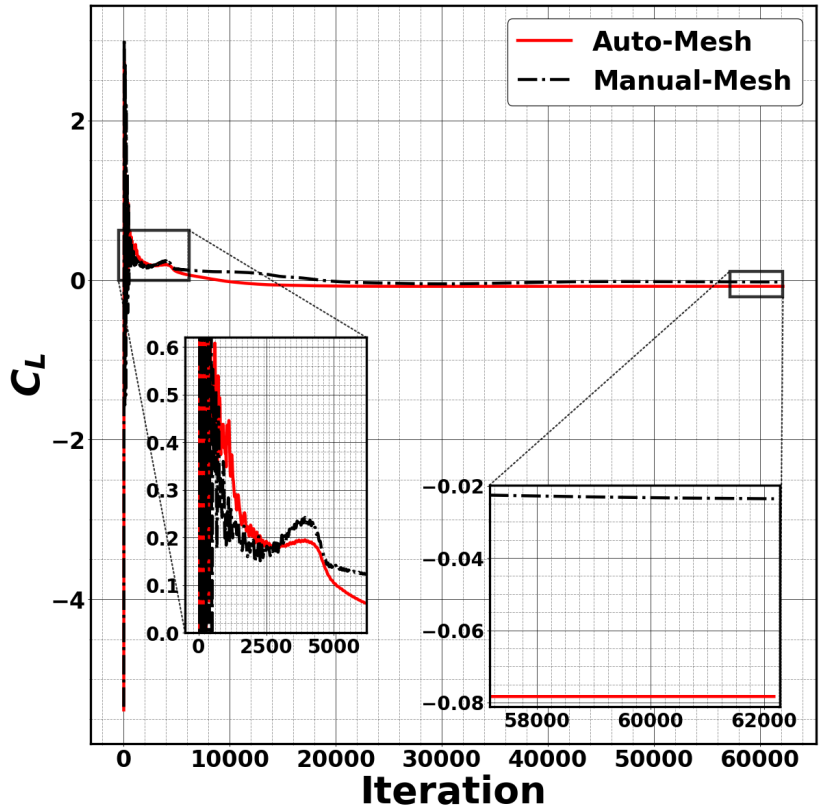
Front Landing Gear

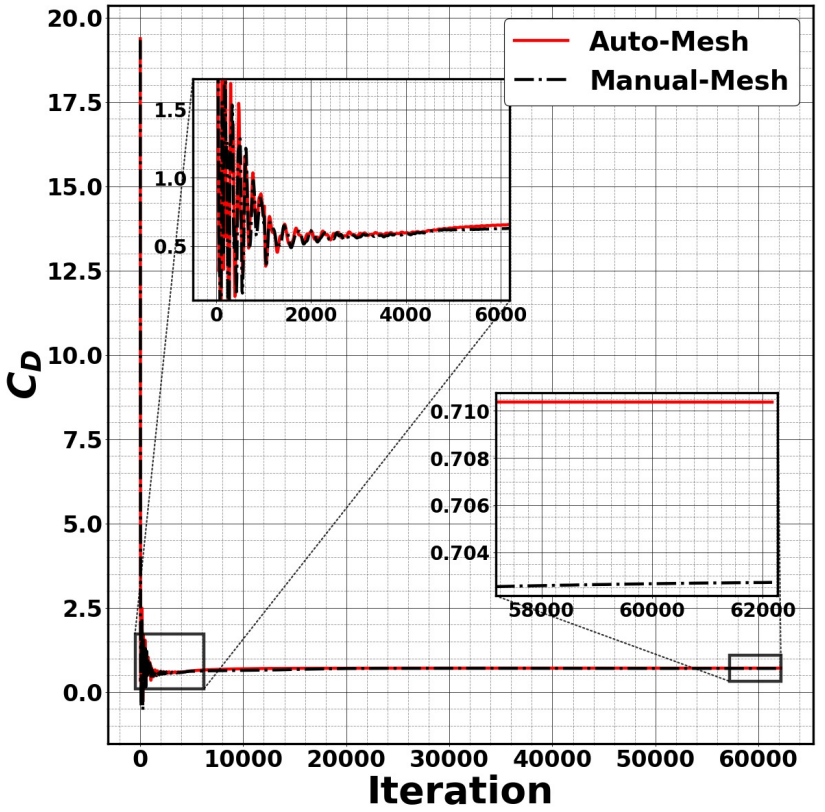
# SIDE-BY-SIDE
## COMPUTATIONAL EFFICIENCY

| | | Automatic | Manual |
|---|---|---|---|
| Before MPI-Splitting | Surface Points | 497K | 508K |
| | # Near Body Grids / # Total Grids | 160 / 414 | 80 / 328 |
| | Fringe + Blanked Point Count | 12M | 12.2M |
| | Total Point Count | 47.5M | 48.2M |
| After MPI-Splitting | # Grids | 838 | 823 |
| | Total Point Count | 53.9M | 56.7M |
| | Overset Boundary Exchange Time/Step (s) | $4.1 \times 10^{-2}$ | $3.8 \times 10^{-2}$ |
| | Parallel Efficiency | 94.0% | 91.0% |
| | Wall Time (196 Broadwell Cores, 62K steps) | 10.8 hrs | 11.7 hrs |

# SIDE-BY-SIDE
## CONVERGENCE BEHAVIOR AND AEROLOADS



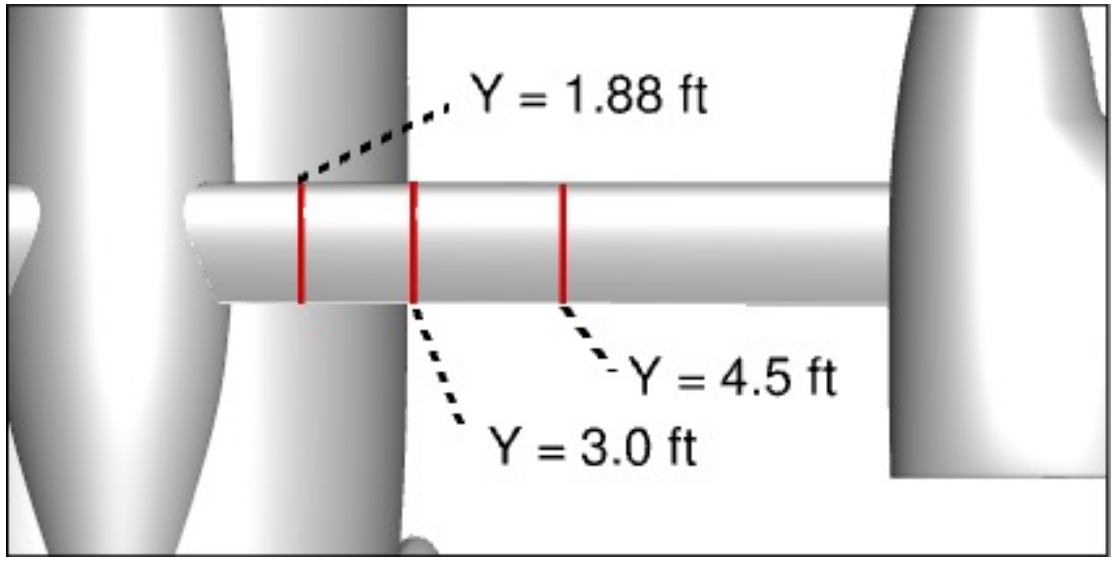



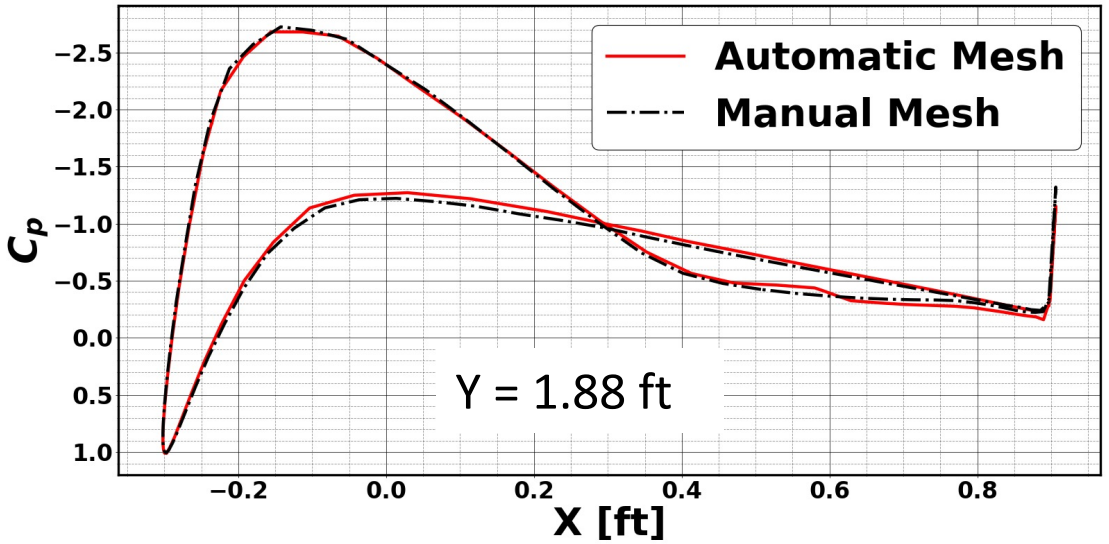



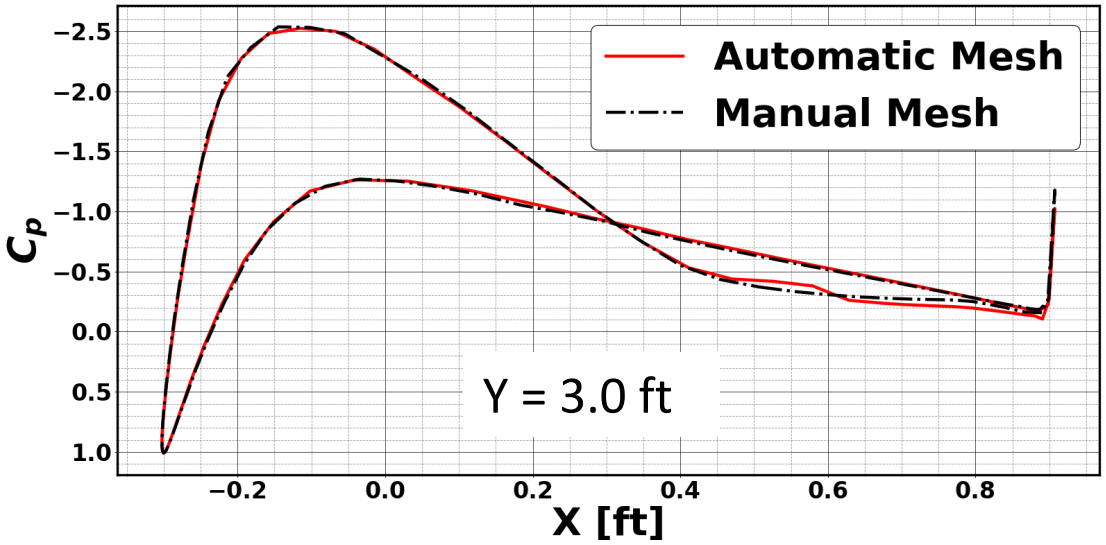

Note: $\mathbf{A_{ref}} = \mathbf{1}\ [m^2]$

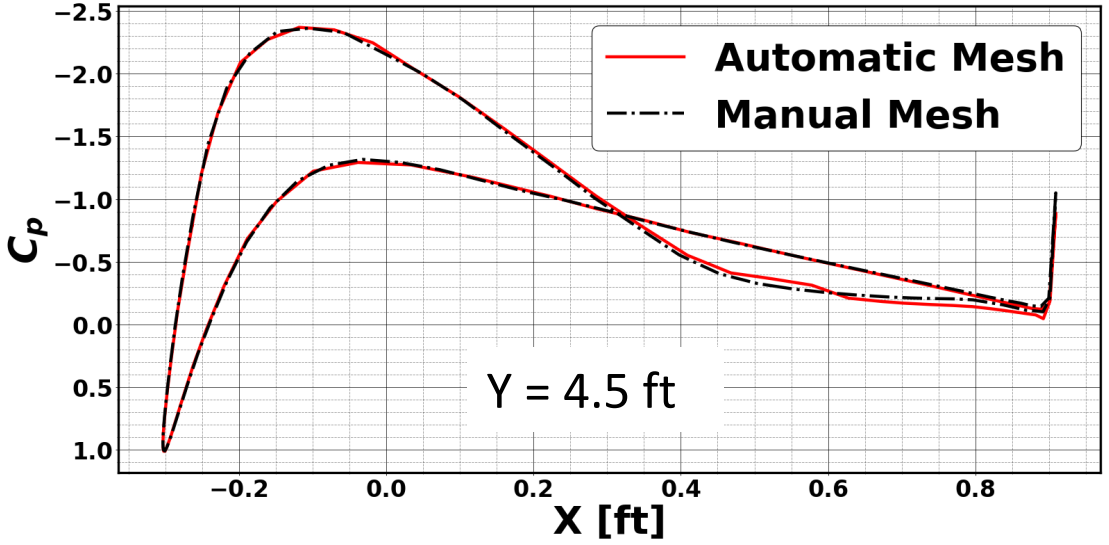
| | $C_L$ | $C_D$ | $C_M$ |
|---|---|---|---|
| Manual Mesh | -0.0229 | 0.7030 | -1.7781 |
| Auto Mesh | -0.0789 | 0.7113 | -1.8387 |
| \|Δ\| | 0.0560 | 0.0083 | 0.0606 |
| % Difference | - | 1.18% | 3.41% |

# SIDE-BY-SIDE
## CP CUTS

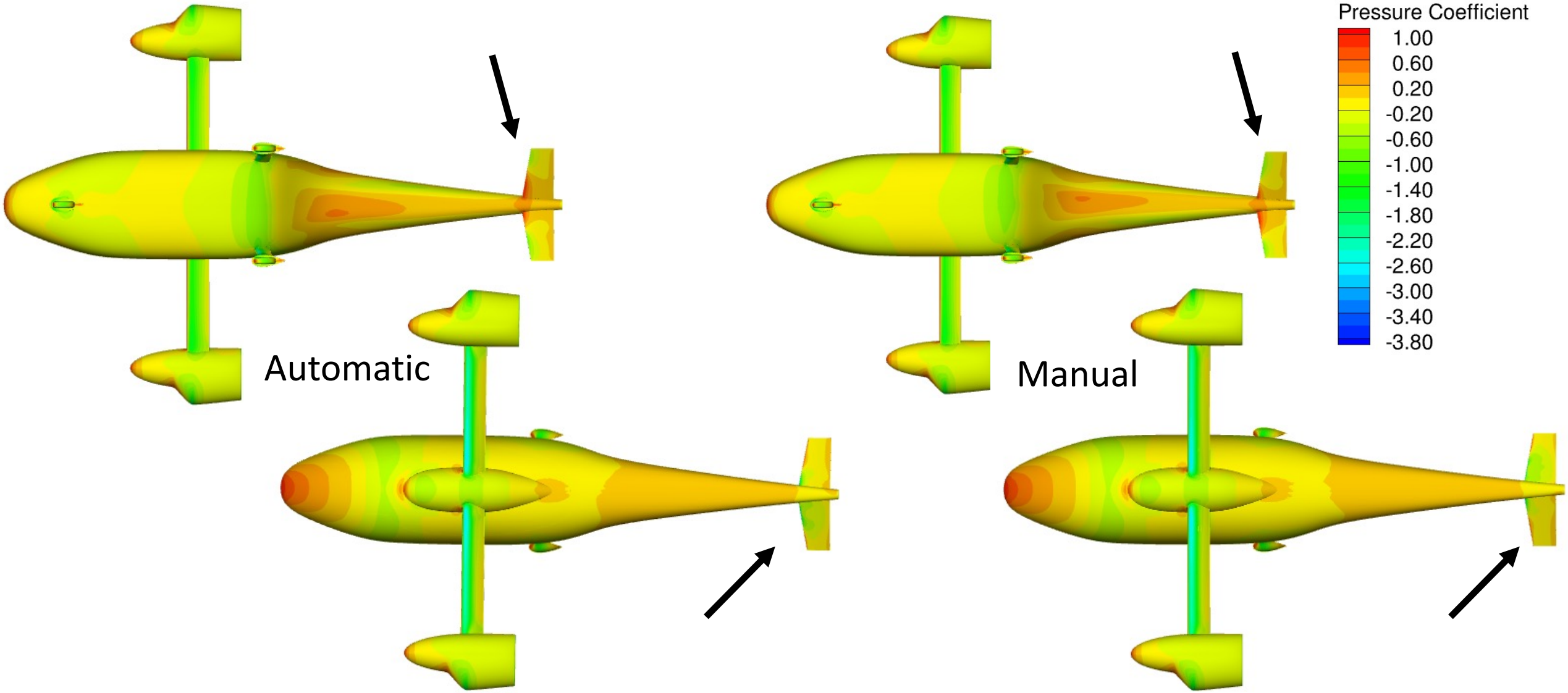


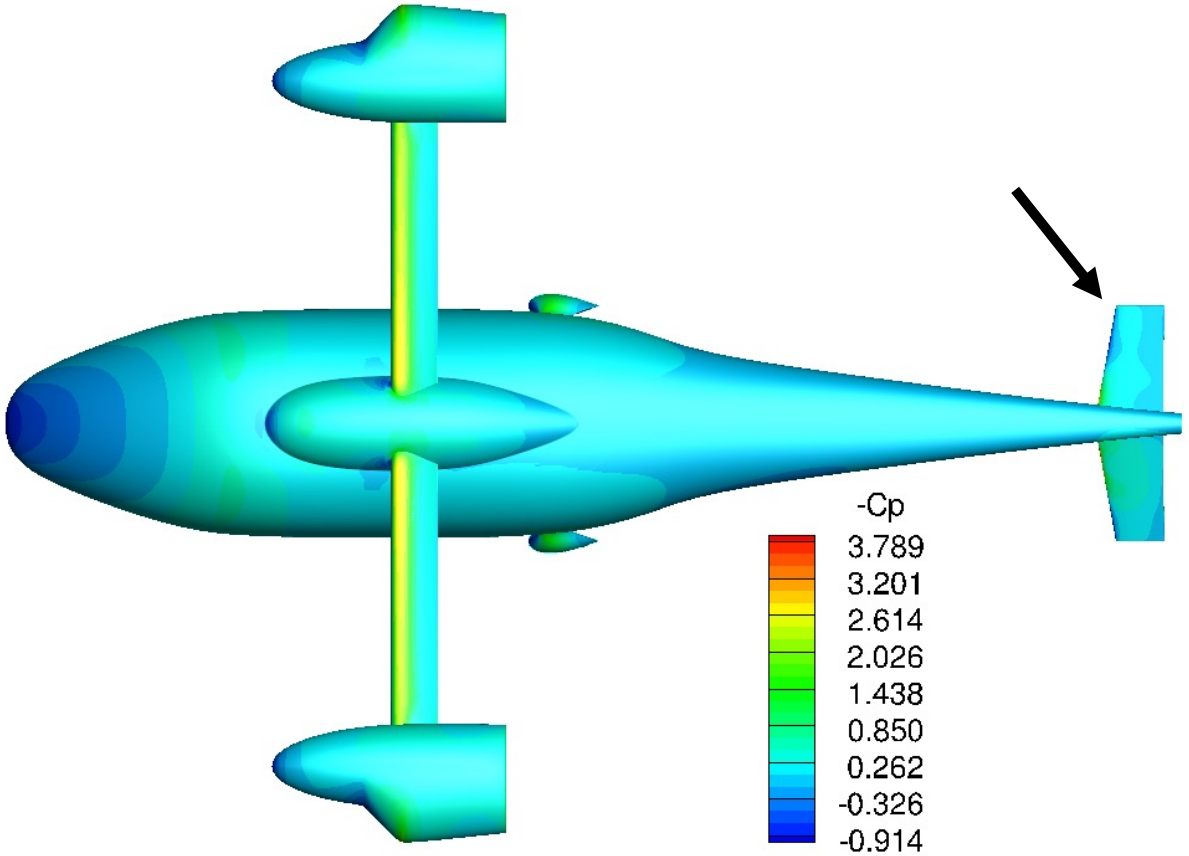
# SIDE-BY-SIDE
## ASYMMETRIC SOLUTIONS



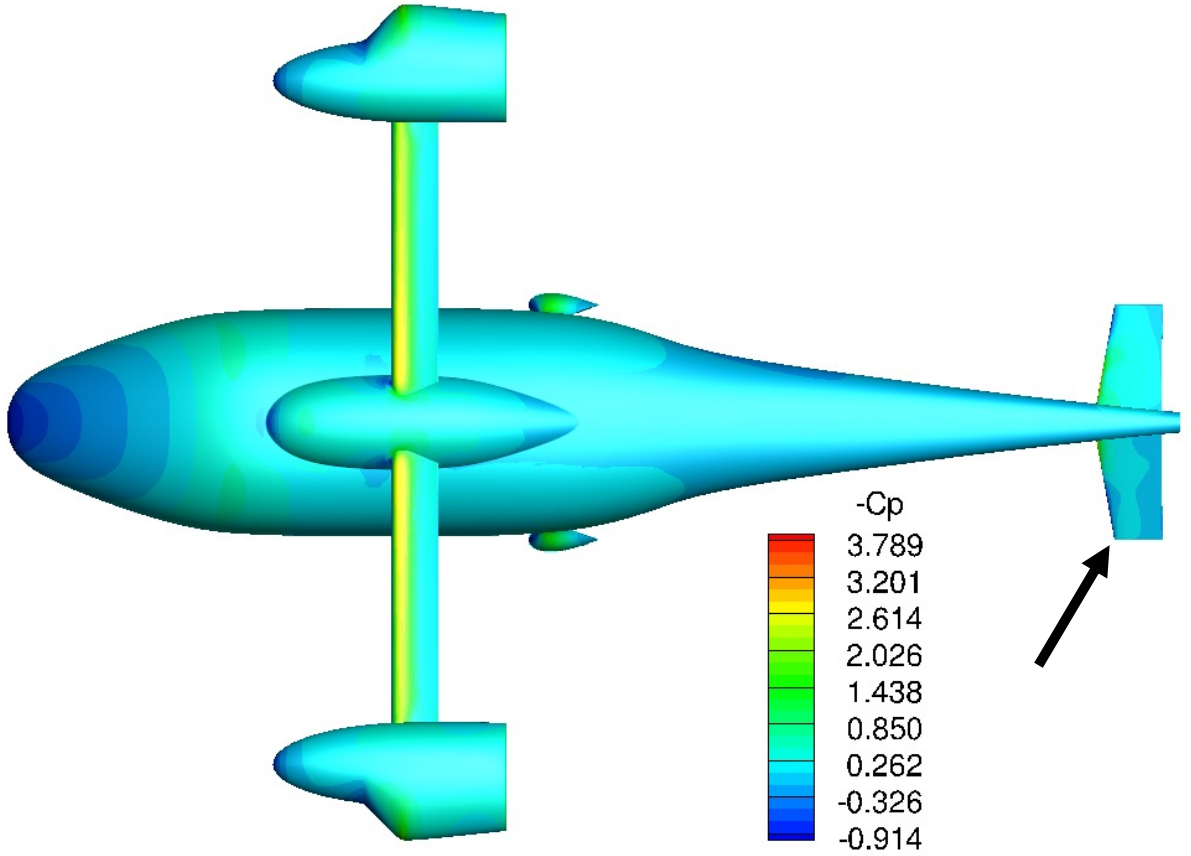

Asymmetric solutions obtained for automatic and manual meshes at $\alpha = 0.0°, \beta = 0.0°$

# SIDE-BY-SIDE
## ASYMMETRIC SOLUTIONS

Solution started at $\beta = 5.0°$, then brought to $\beta = 0.0°$

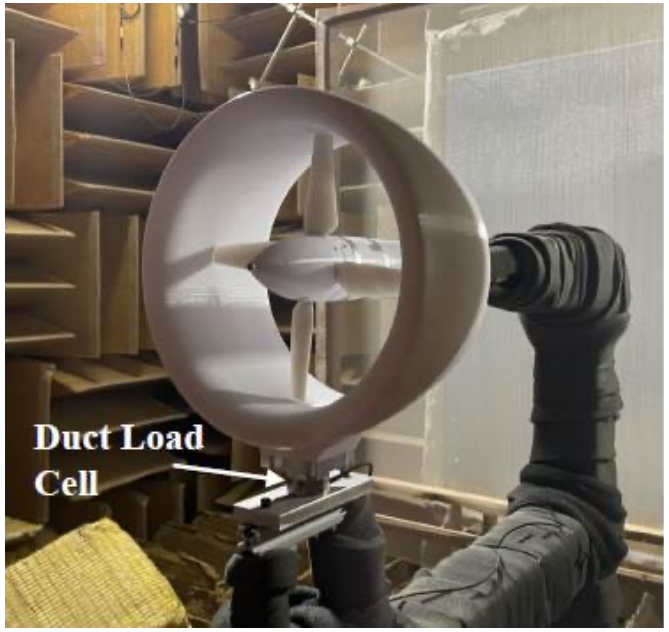


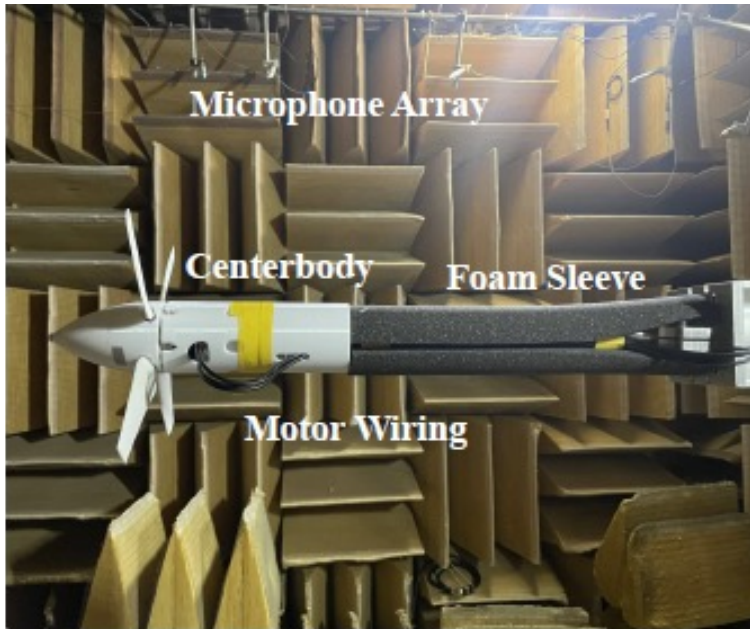

Solution started at $\beta = -5.0°$, then brought to $\beta = 0.0°$



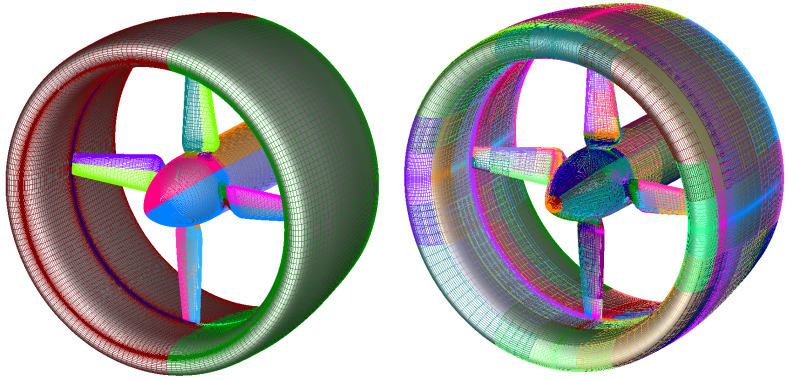

Steady RANS solutions exhibit asymmetric non-unique solutions in tail region at $\alpha = 0.0°$, $\beta = 0.0°$

# SMALL DUCTED PROPELLER





Manual



Automatic

White part: Initial geometry provided & mesh generation domain

Potential sources of difference between CFD and experiment

- Support hardware
- Blade pitch mount angle uncertainty (+/- 1 deg.)
- Blade roughness

*Zawodny, N., Schiller, N. H., Pettingill, N. A., and Medina, G. L., "Aerodynamic and Acoustic Characterization of a Ducted Propeller in a Small Hover Anechoic Chamber," Tech. Rep. NASA-TM-2023-0006669 (manuscript in preparation), NASA Langley, 2023. 36*

# SMALL DUCTED PROPELLER
## MESHING TIME & EFFORT

| Flow Parameters | Value [7] |
|---|---|
| $V_\infty$ | 0 m/s |
| $P_\infty$ | 101815 Pa |
| $T_\infty$ | 297.26 K |
| $\rho_\infty$ | 1.19 kg/m$^3$s |
| $\alpha$ | 0.0$^o$ |
| Rotational Speed | 8167 RPM |

| Steps | Automatic | Manual |
|---|---|---|
| Surface Meshing | 28 s(C) | 3 days (M) |
| Volume Meshing | 1.5 min (C) | 1 day (M) |
| Volume Mesh Repair | 2 days (M) | - |
| Domain Connectivity | 1 day (M) | 3 hrs (M) |
| Surface Integration Inputs | 4 hrs (M) | 1 hr (M) |
| Flow Solver Inputs | 30 min (M) | 30 min (M) |
| Total Turnaround Time | ~ 3 days | ~ 1.5 wks |

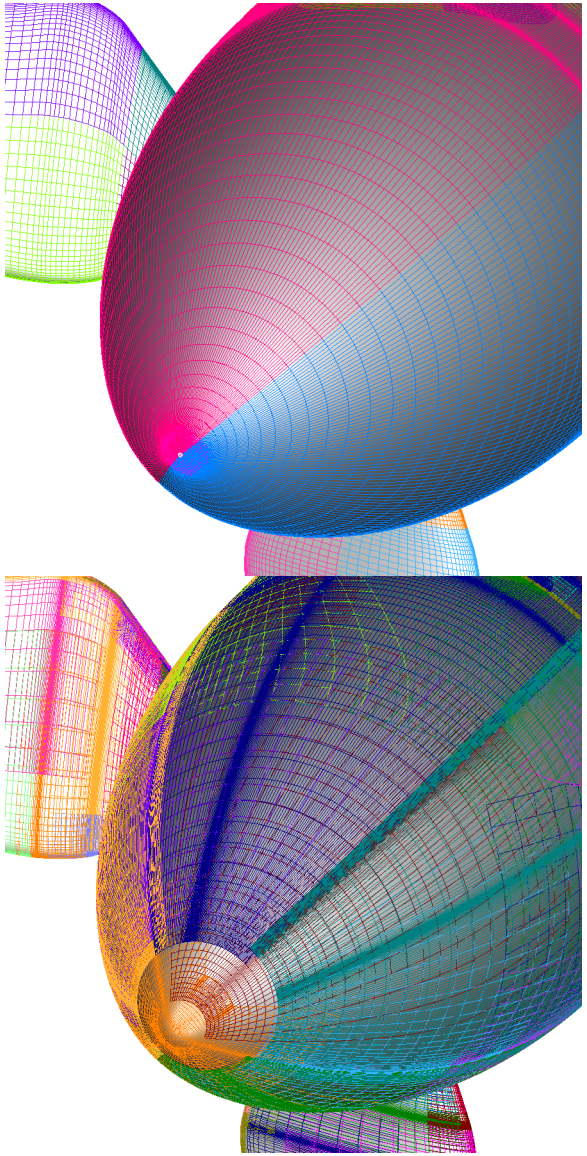
(C): CPU wall-clock time
(M): Manual labor time (assuming 8hrs/day for an intermediate user)

# SMALL DUCTED PROPELLER
## GRID COMPARISON

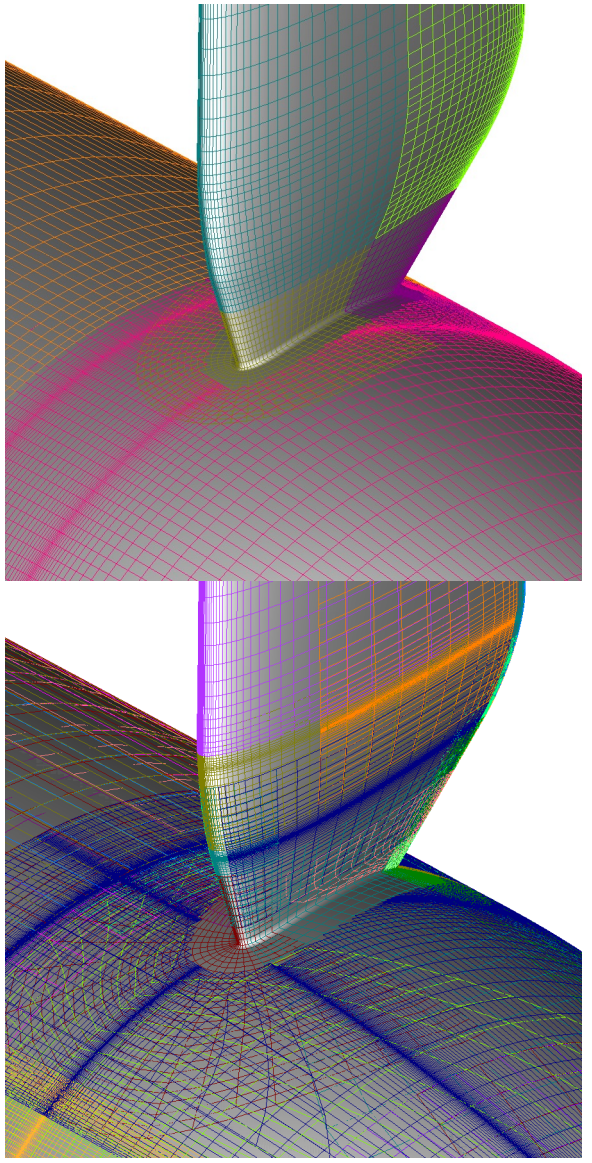


Manual

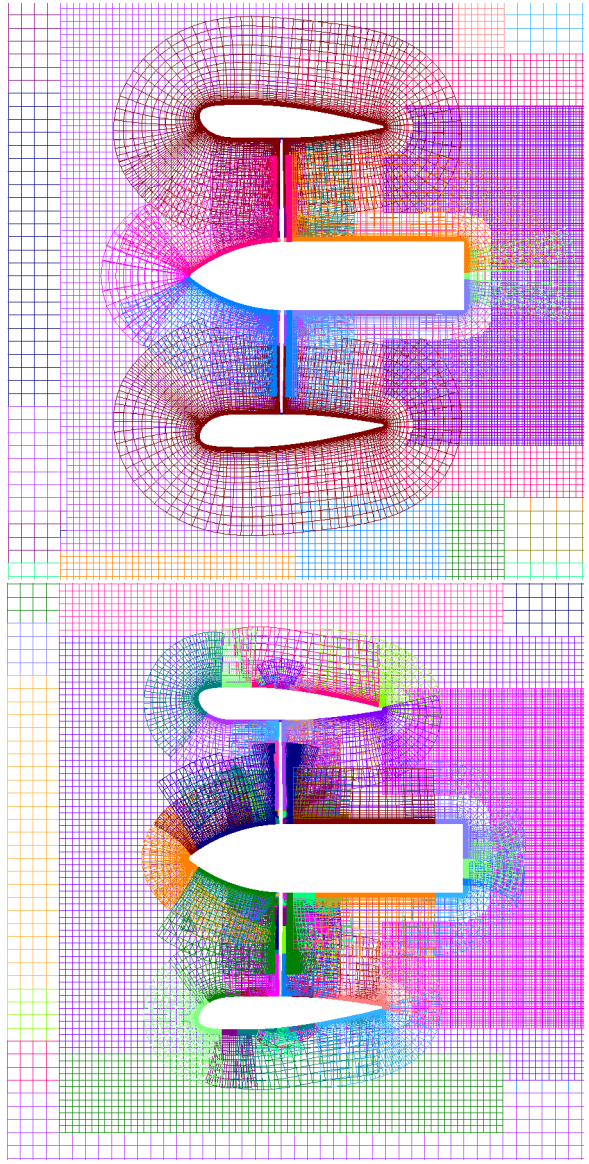
Automatic



Rotor Hub



Blade Hub Junction



Symmetry Cut (Y=0)

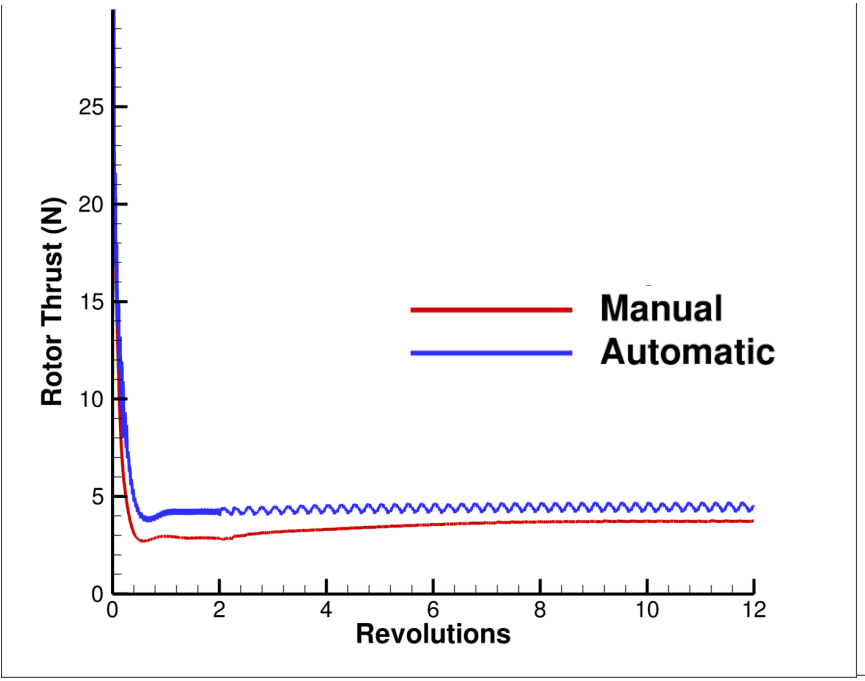
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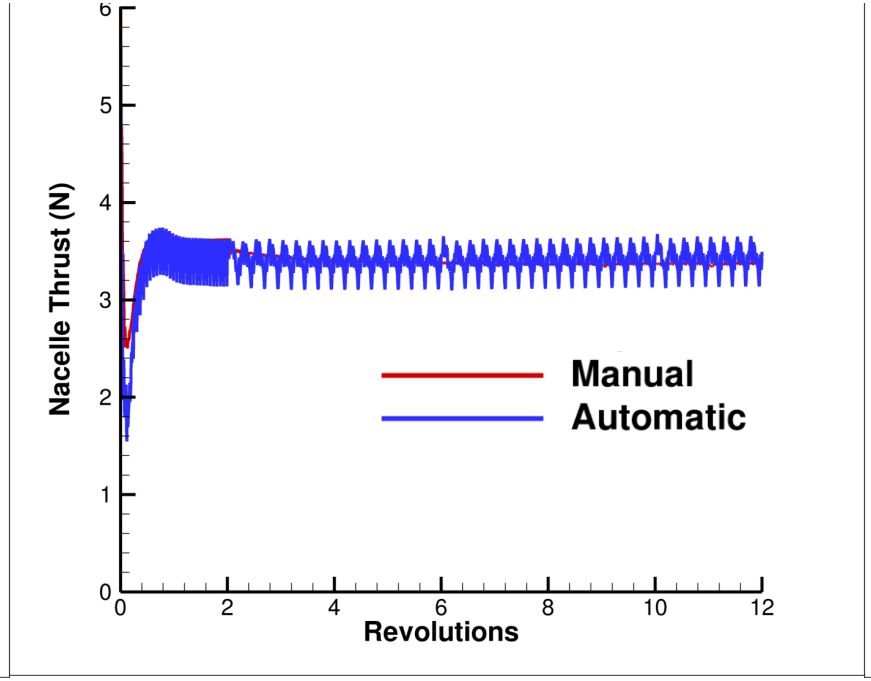
# SMALL DUCTED PROPELLER
## COMPUTATIONAL EFFICIENCY

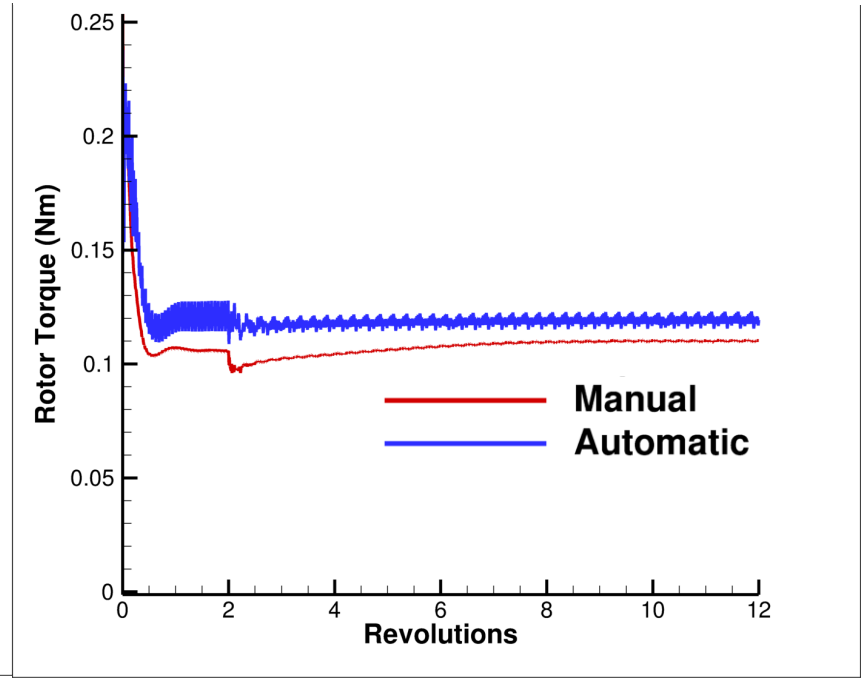
| | | Automatic | Manual |
|---|---|---|---|
| Before MPI-Splitting | # Near Body Grids / # Total Grids | 265 / 361 | 38 / 157 |
| | Total Point Count | 17.4M | 10.1M |
| After MPI-Splitting | # Grids | 434 | 236 |
| | Total Point Count | 18.6M | 11.2M |
| | # Cores (Haswell) | 72 | 48 |
| | Overset Boundary Exchange Time/Step (s) | $4.55 \times 10^{-1}$ | $4.60 \times 10^{-1}$ |
| | Parallel Efficiency | 84.1% | 80.4% |
| | CPU Time/Rev | 792 hrs | 648 hrs |
| | Residual Drop Over 15 Sub-Iterations | 3.7 | 3 |

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# SMALL DUCTED PROPELLER
## AEROLOADS: MANUAL MESH VS AUTOMATIC MESH

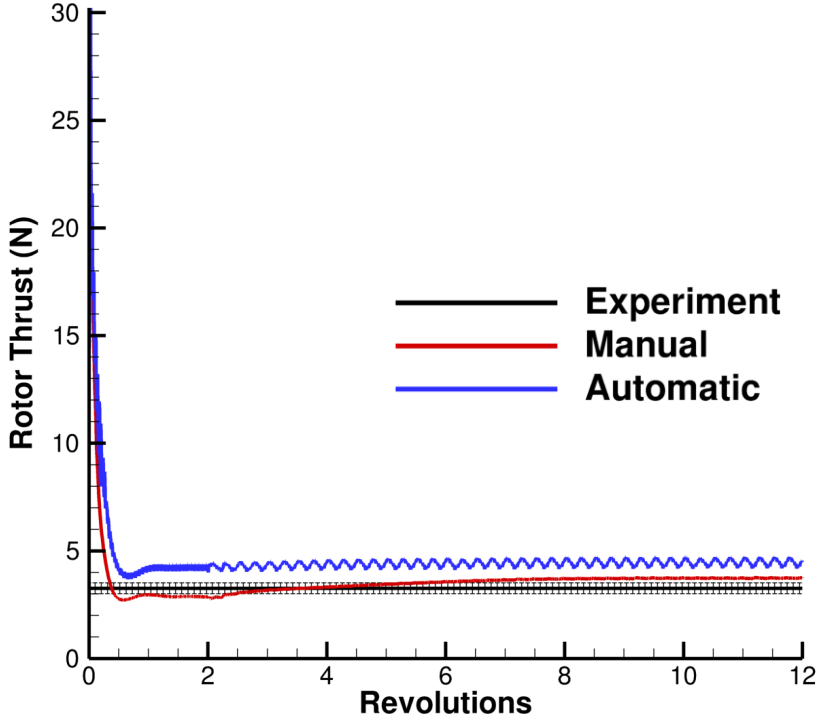


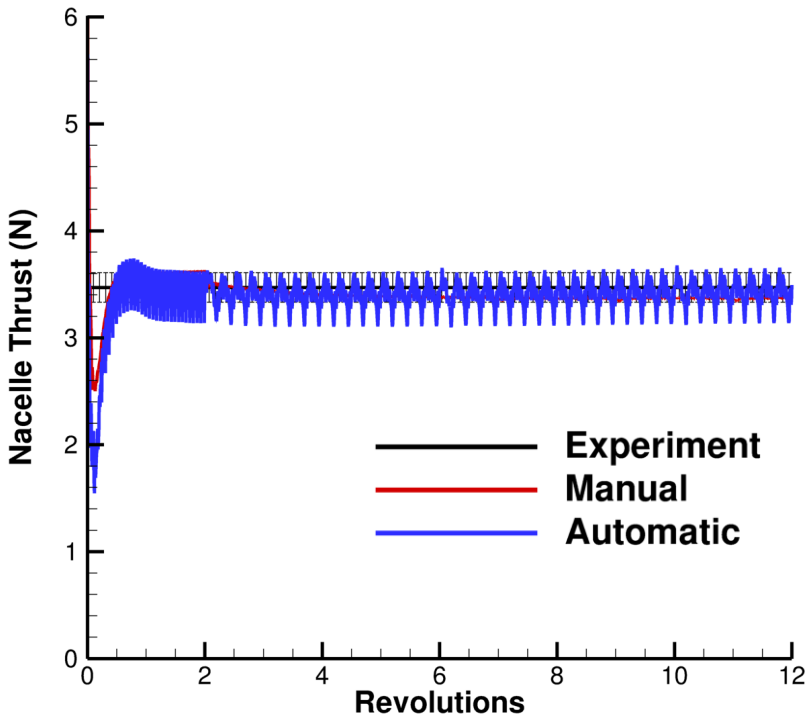



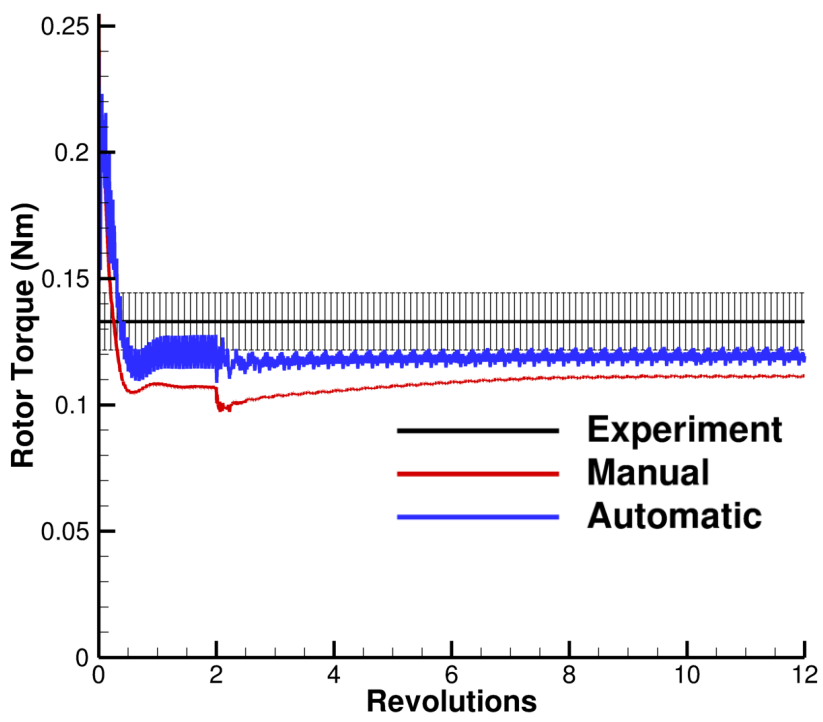




| | Automatic | Manual | % Diff |
|---|---|---|---|
| Rotor Thrust (N) | 4.48 | 3.74 | 20 |
| Nacelle Thrust (N) | 3.43 | 3.38 | 1 |
| Rotor Torque (Nm) | 0.120 | 0.111 | 8 |

# SMALL DUCTED PROPELLER AEROLOADS: CFD VS EXPERIMENT




| | Automatic | Manual | Experiment |
|---|---|---|---|
| Rotor Thrust (N) | 4.48 | 3.74 | 3.26 |
| Nacelle Thrust (N) | 3.43 | 3.38 | 3.47 |
| Rotor Torque (Nm) | 0.120 | 0.111 | 0.133 |

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# CONCLUDING REMARKS

- Investigated flow solution comparisons between automatically and manually generated overset meshes for four test cases
- Automatic meshes show comparable capability to manual meshes in flow solution computation (aerodynamic loads, convergence history, cost, efficiency)
- No significant penalties observed from near-body grid fracturing
- Hybrid auto/manual approach enables significant reductions in turnaround time for overset CFD analysis
- Grid refinement mesh family can be created using the automatic meshing tools with consistent results

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# ACKNOWLEDGEMENTS


## Funding

NASA Revolutionary Vertical Lift Technology (RVLT) Project
NASA Transformational Tools and Technologies (TTT) Project

## Computational Resources

NASA Advanced Supercomputing (NAS) facility

Dr. Tom Pulliam, for insightful discussions on running test cases in OVERFLOW