Computational Analysis on the Effects of High-Lift Propellers and Wingtip Cruise Propellers on X-57

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Seung Y. Yoo
NASA Armstrong Flight Research Center, Edwards, CA 93523

Jared C. Duensing
NASA Ames Research Center, Moffet Field, California, 94035

Karen A. Deere, Jeffrey K. Viken
NASA Langley Research Center, Hampton, VA 23681

Michael Frederick
NASA Armstrong Flight Research Center, Edwards, CA 93523

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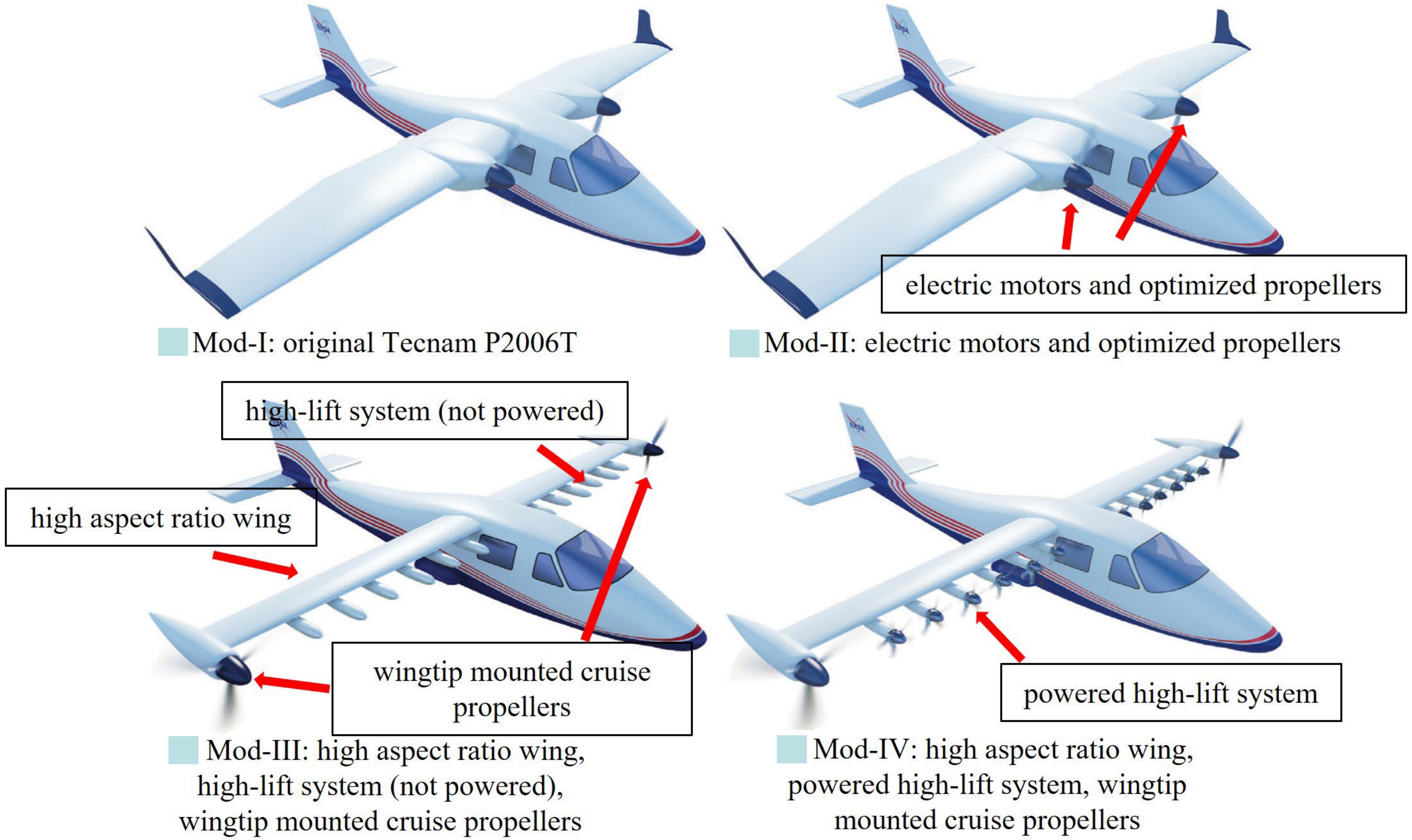
Outline

- Introduction
- Computational Tools
- Results
- Conclusion

Introduction – X-57

- Demonstrate technologies intended to improve aerodynamic efficiency and reduce carbon footprint
- Separated into multiple phases or modifications, denoted as “Mod”
    - Electrical motors for propulsion
    - Optimized high aspect ratio wing and high lift nacelle
    - Wingtip mounted cruise propellers for reducing induced drag
    - High-lift system to augment flow to generate more lift



Introduction – Mod-III

- High-aspect ratio wing
  - C_{mac} = 2.13 ft (48.4% of original wing)
  - AR = 15 (170.4% of original wing)
  - Wing area = 66.7 ft^2 (58% of original wing)
- Wingtip mounted cruise propellers
  - Powered by electric motor
  - 3 blades per propellers
  - 5 ft radius
  - Rotate outboard direction

https://www.nasa.gov/specials/X57/modification.html#3

Introduction – Mod-IV

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  - C_{mac} = 2.13 ft (48.4% of original wing)
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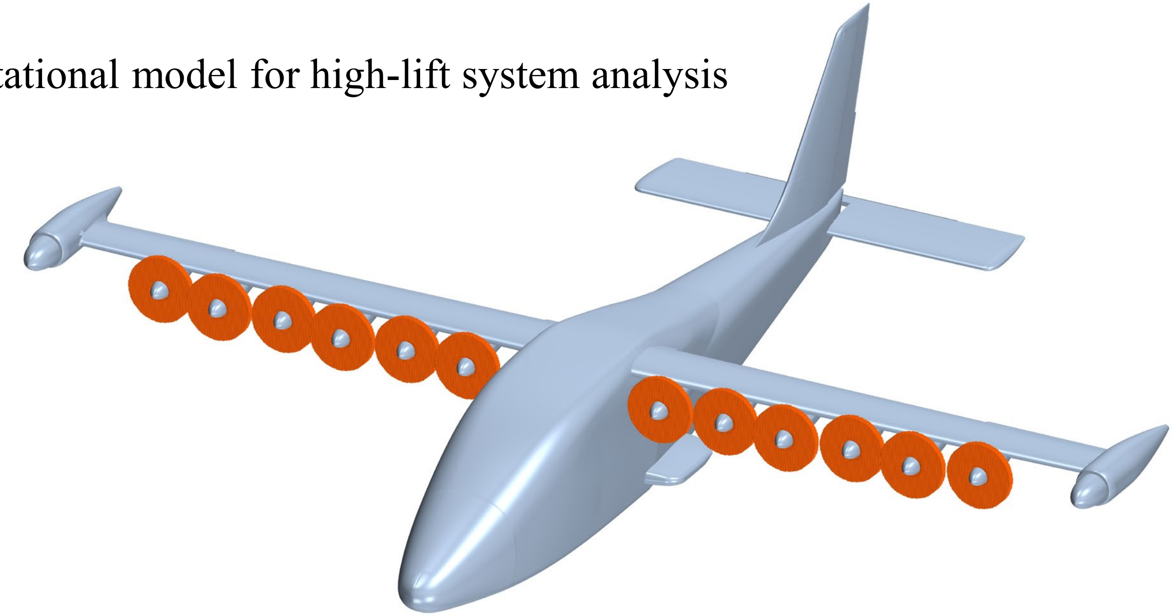
  - Wing area = 66.7 ft^2 (58% of original wing)
- Wingtip mounted cruise propellers
  - Powered by electric motor
  - 3 blades per propellers
  - 5 ft radius
  - Rotate outboard direction
- High-Lift System
  - 12 propellers (6 each side)
  - 5 blades per propeller
  - 1.89 ft radius
  - Rotate outboard direction
  - Powered on during terminal phase of flight

https://www.nasa.gov/specials/X57/modification.html#4

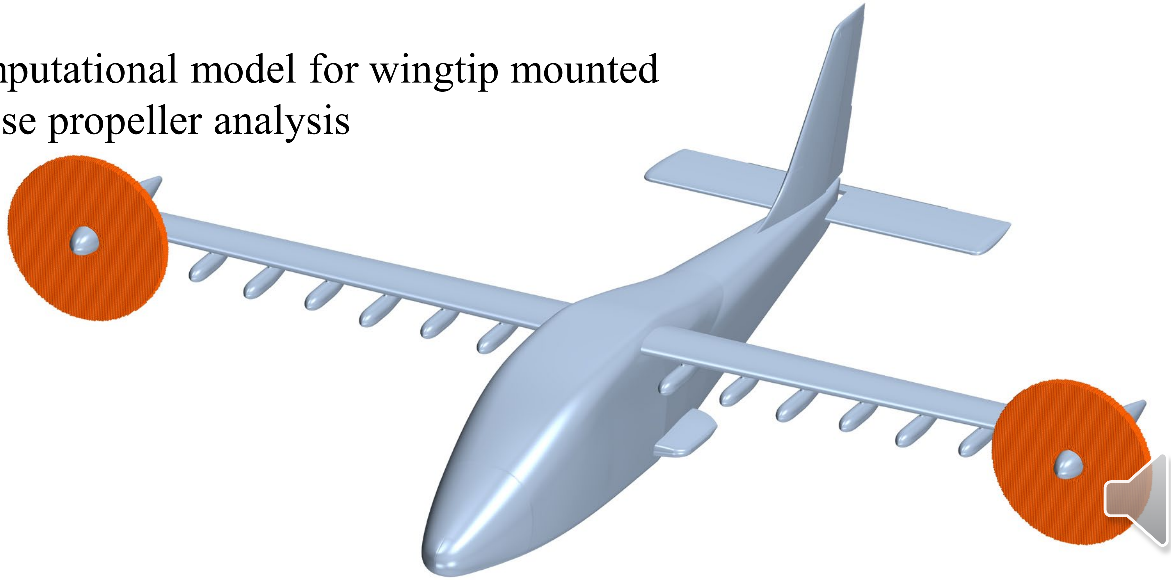
Introduction

- Study focused on effects of high-lift propellers and wingtip mounted cruise propellers
- High-lift propellers and wingtip mounted cruise propellers modeled separately
- Understanding of the aerodynamics of the vehicle
- Performance benefit

computational model for high-lift system analysis



computational model for wingtip mounted cruise propeller analysis



Computational Tools

STAR-CCM+ (v13.04.10)

- Grid
  - Unstructured polyhedral mesh with prism layer
- Solver
  - Steady state RANS
  - 2nd order Roe flux-differencing spatial scheme with implicit Gauss-Siedel relaxation scheme
  - SA-RC-QCR
- Propeller modeling
  - Actuator disk with X-57 specific performance curve based on blade-element-momentum-theory for high-lift propellers and Goldstein distribution for cruise propellers

Launch Ascent Vehicle Analysis Framework (LAVA)

- Grid
  - Structured, curvilinear, overset grids
- Solver
  - Steady state RANS structured curvilinear solver
  - 2nd order Roe flux discretization with Koren limiter and Alternating Line-Jacobi method
  - SA-RC-QCR
- Propeller modeling
  - Actuator disk with X-57 specific performance curve based on blade-element-momentum-theory for high-lift propellers and Goldstein distribution for cruise propellers

USM3D

- Grid
  - Unstructured tetrahedral mesh
- Solver
  - Time-accurate RANS solver with global time-marching scheme
  - 2nd order Roe flux-differencing spatial scheme with implicit Gauss-Seidel scheme
  - SA-QCR
- Propeller modeling
  - Actuator disk with triangular distribution for high-lift propellers and cruise propellers

Kestrel

- Grid
  - Mixed element, unstructured tetrahedral core mesh with prism layer
- Solver
  - Time-accurate RANS solver with global time-marching scheme
  - HLLE++ with implicit Gauss-Seidel method
  - SA-RC
- Propeller modeling
  - Actuator disk with triangular distribution for high-lift propellers and cruise propellers

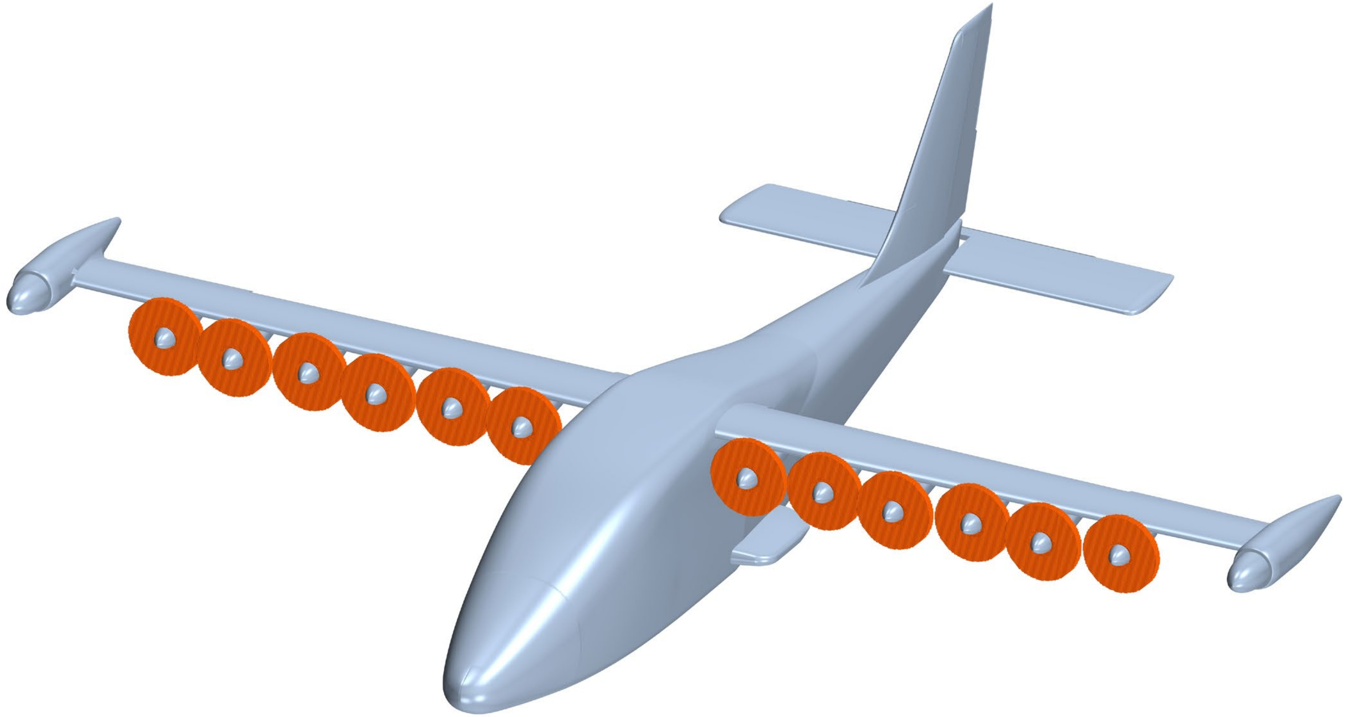
Results

- High-Lift Propellers
- Wingtip Mounted Cruise Propeller

High-Lift Propeller Results

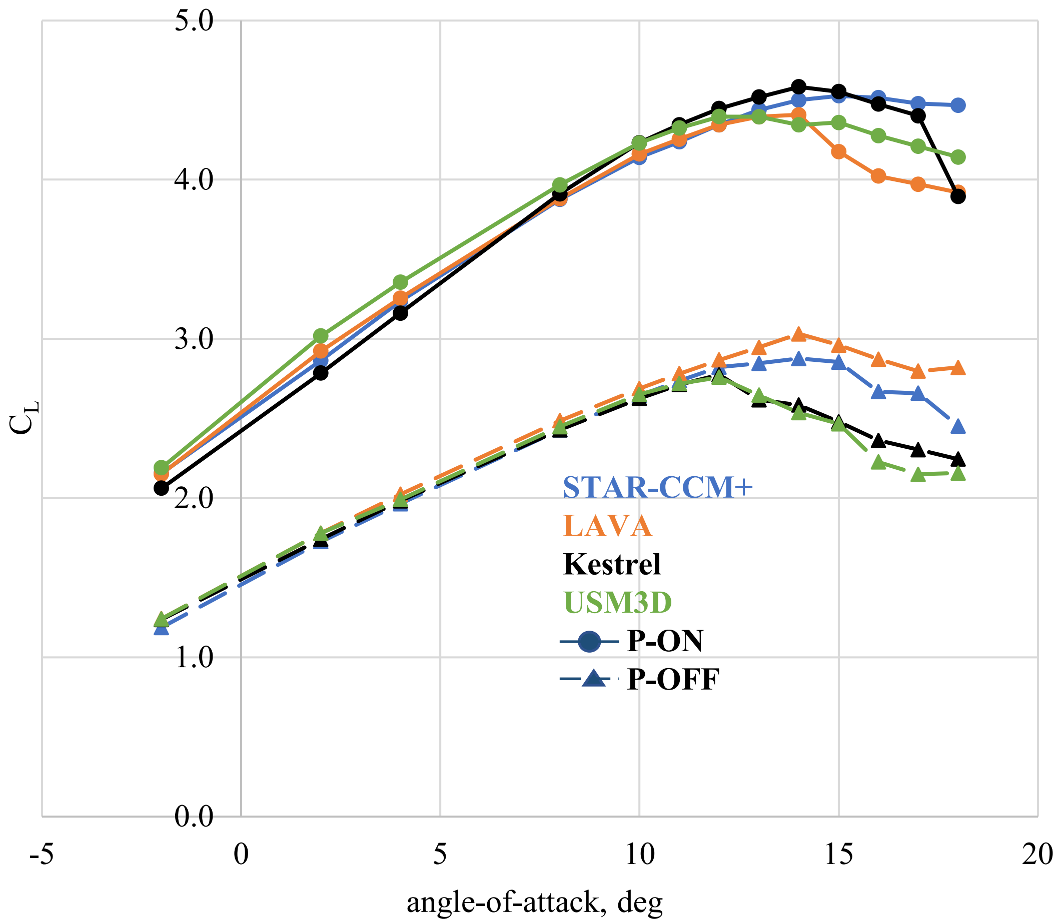
Results – High-Lift Propellers

- Atmospheric Condition
  - Altitude 2500 ft, Mach 0.092, 58 KCAS
  - Density 2.2078E-3 kg/m^3
  - Static pressure 92499.6 Pa
  - Static temperature 283.2K
  - Reynolds number 6.1E5
- Aircraft configuration
  - All control surfaces at 0° deflection
  - Flap 30° deflection
  - High-lift system powered on
    - 49.1 lbf thrust (maximum thrust)
    - Propellers rotate outboard direction
  - Cruise propellers not modeled



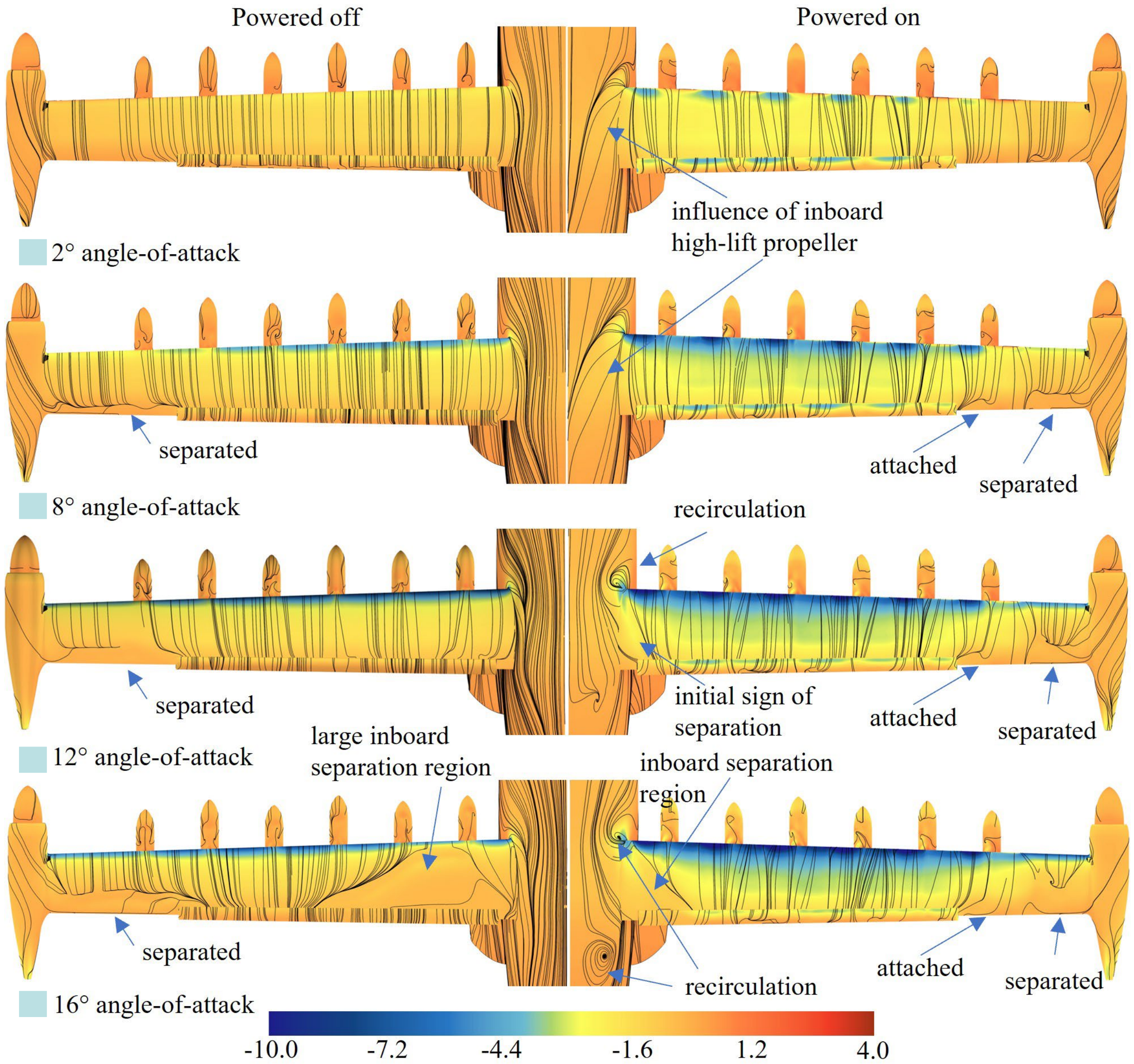
Results – High-Lift Propellers
Lift Coefficient

- Power–off results
  - Shows good comparison in the linear region
  - Difference in $C_{L,max}$ and angle-of-attack for it
  - Sharper drop in C_L for Kestrel and USM3D compared to STAR-CCM+ and LAVA
- Power-on results
  - Increased lift and lift-curve-slope per angle-of-attack
  - As much as 65.4% increase $C_{L,max}$
  - Reduced loss of lift post $C_{L,max}$
  - Variation in C_L in linear region due to difference in performance curve in actuator disk



Results – High-Lift Propellers
Comparison Between Powered On and Powered Off Configuration

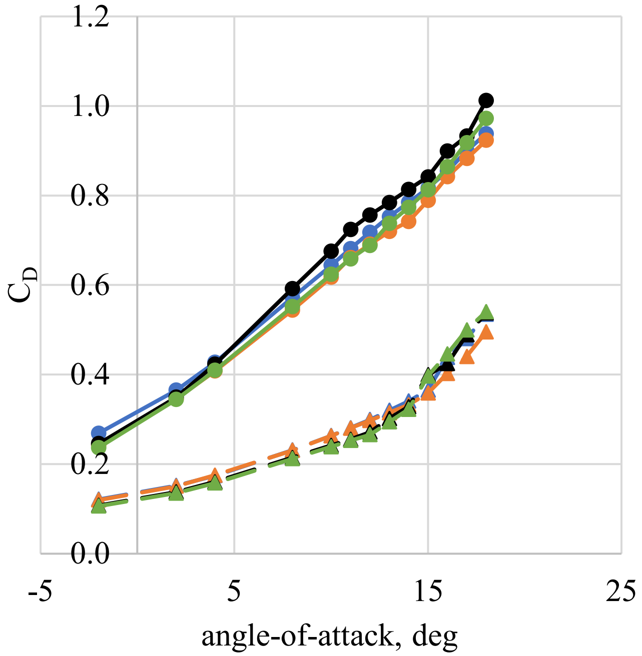
Pressure Coefficient Contour and Surface Streamline

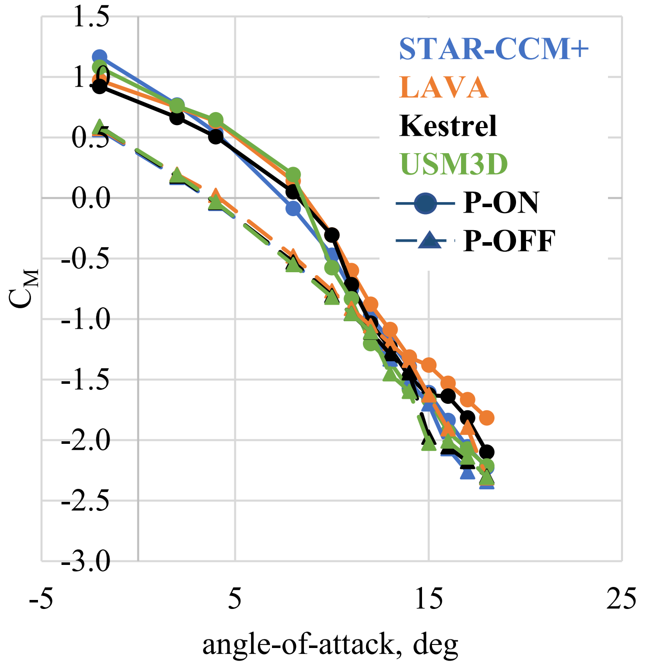


Results – High-Lift Propellers
Drag and Pitching Moment Coefficients

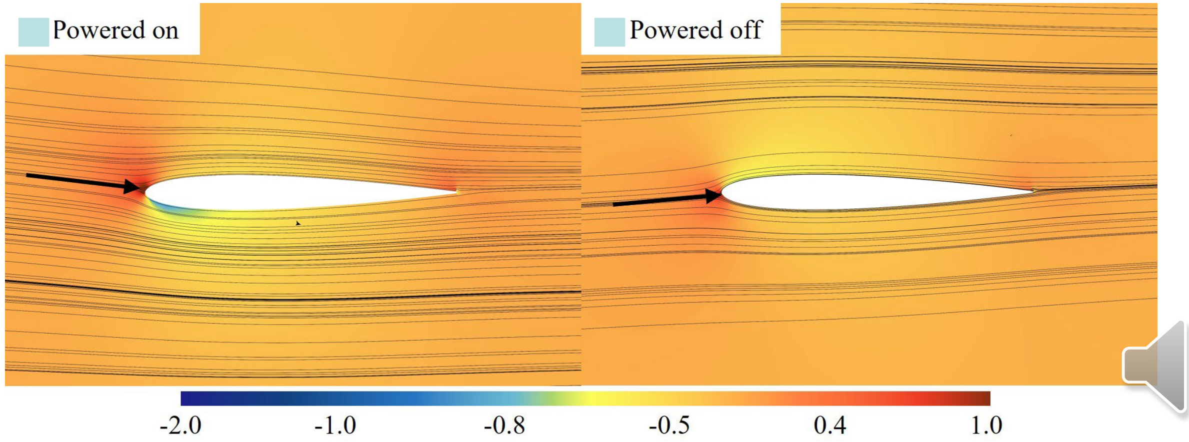
- Powered on configuration has more nose-up pitching moment
  - Less lift generated by stabilator
  - Higher drag on wing, since it sits higher than the MRC, will create nose-up pitching moment

- Effect of high-lift propellers diminishes with increase in angle-of-attack
  - Less influence on stabilator





Stabilator Section: Pressure Coefficient Contour and Streamline
8° angle-of-attack



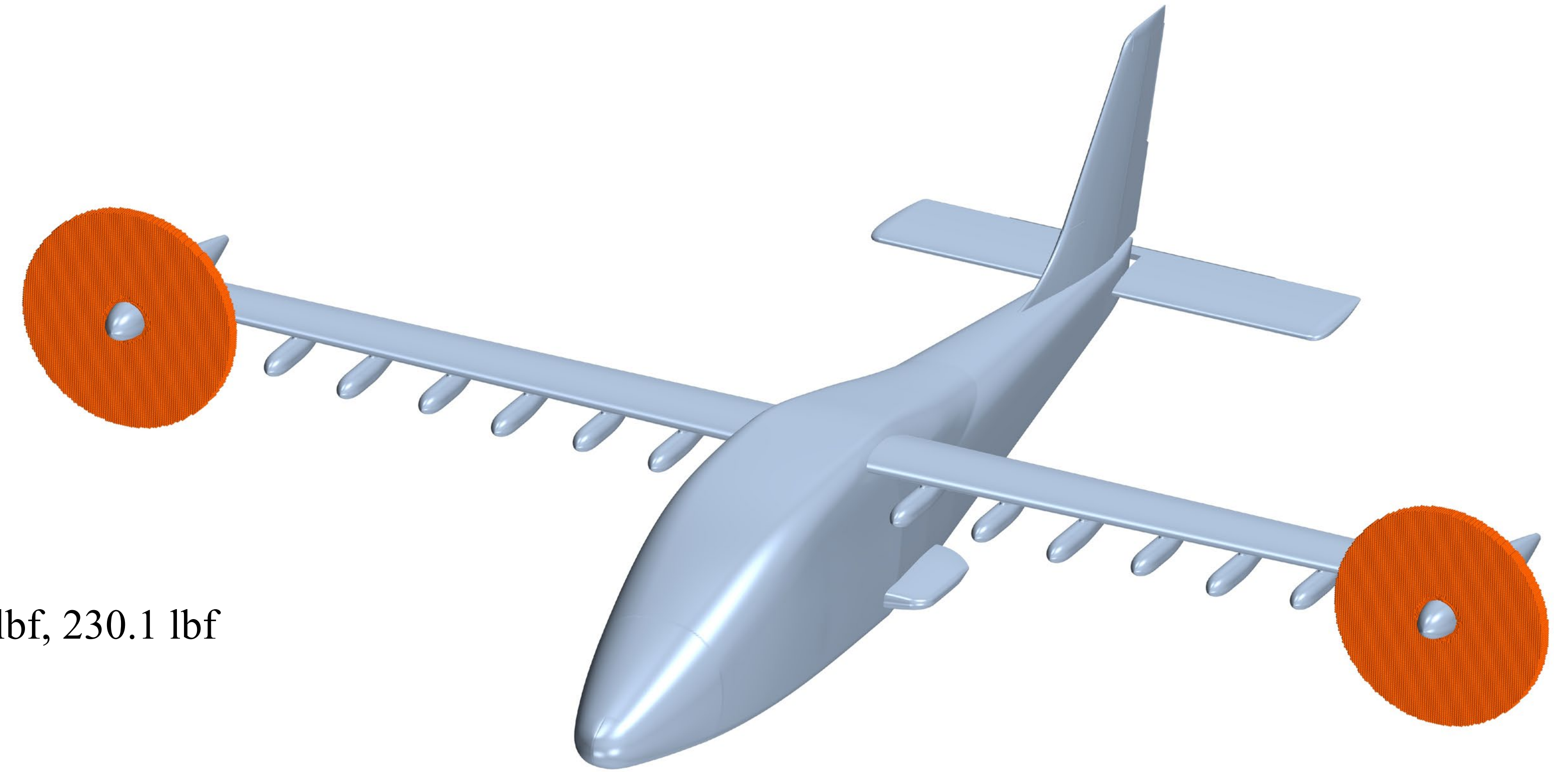
Wingtip Mounted Cruise Propeller Results

Results – Cruise Propellers

- Atmospheric Condition
  - Altitude 8000 ft, Mach 0.233, 133 KCAS
  - Density 1.8628E-3 kg/m^3
  - Static pressure 75262.3 Pa
  - Static temperature 272.3K
  - Reynolds number 1.32E6
  - 2° angle-of-attack

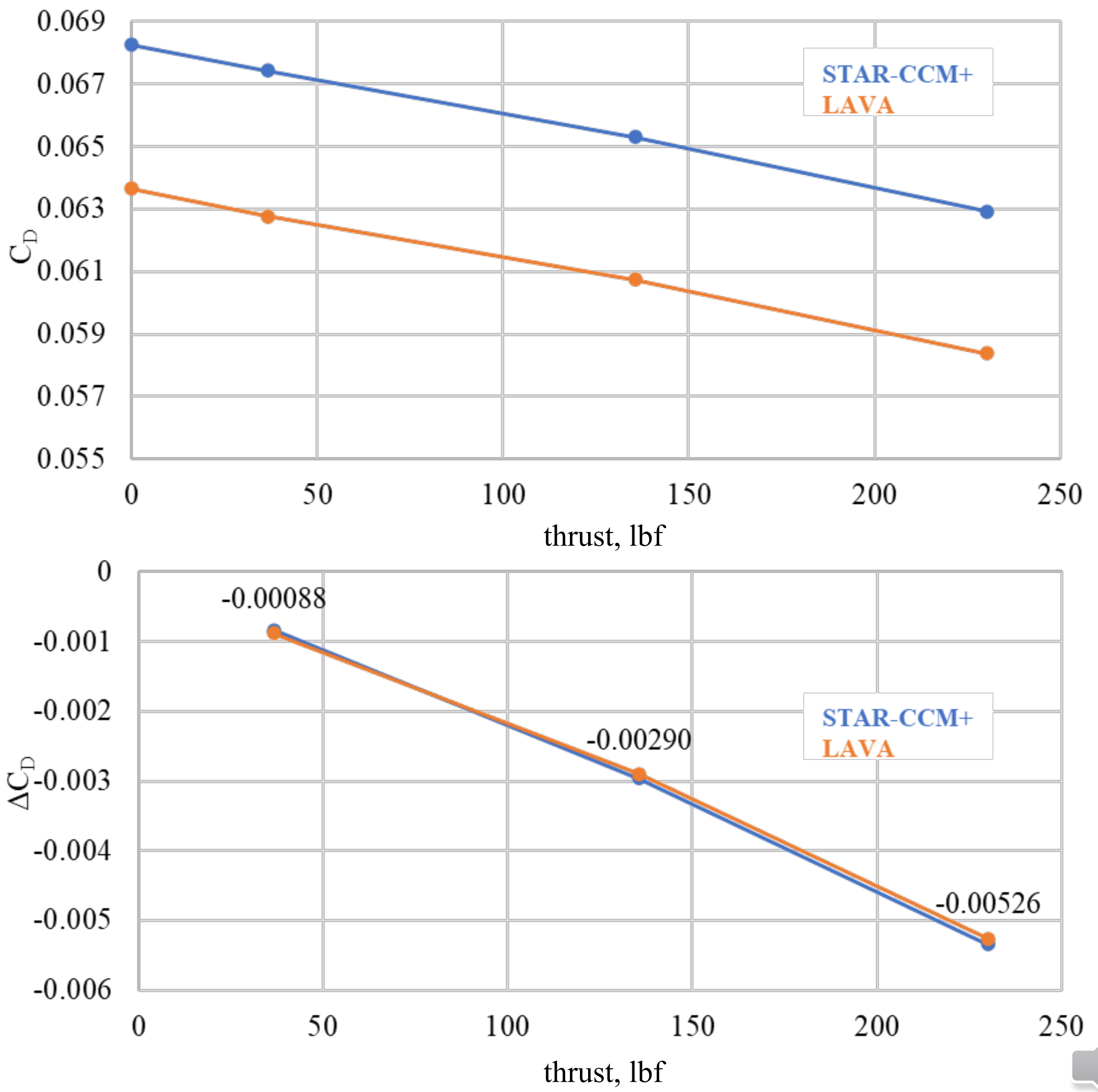
- Aircraft configuration
  - All control surfaces at 0° deflection
  - Flap 0° deflection
  - Cruise propellers Thrust: 36.6 lbf, 135.6 lbf, 230.1 lbf
  - High-lift propellers not modeled

- Results focused on drag



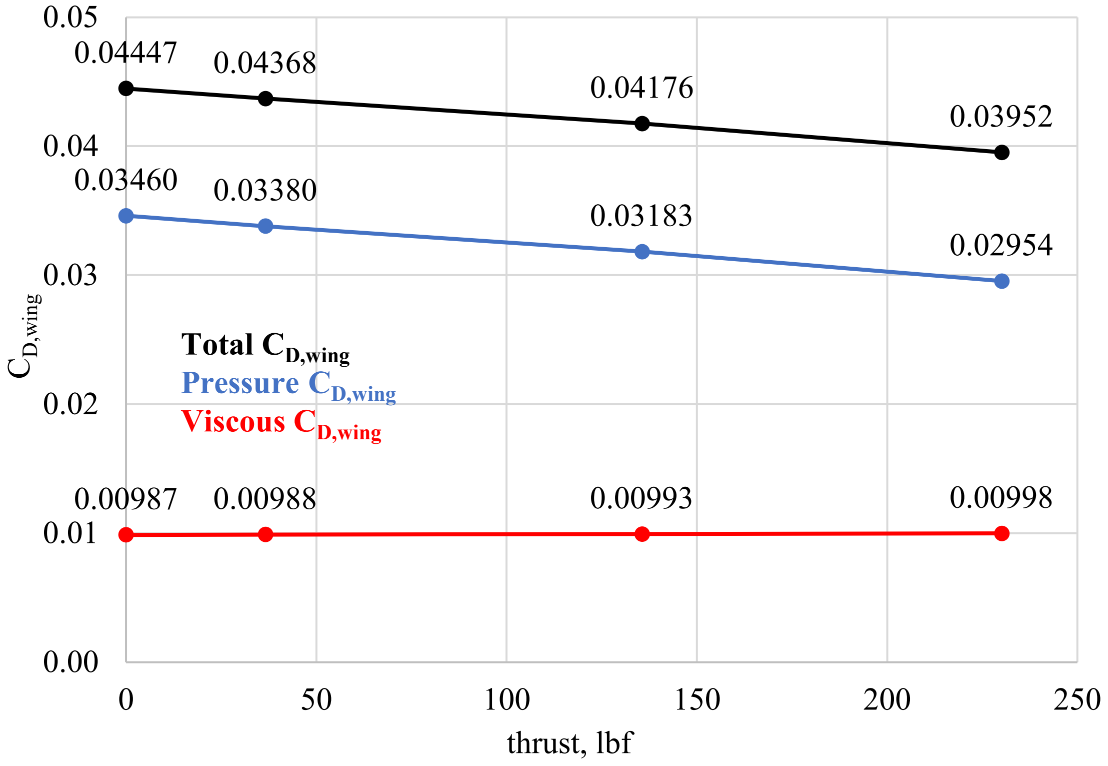
Results – Cruise Propellers
Aircraft Drag Coefficient

- STAR-CCM+ results show higher C_D compared to LAVA, but 2 solvers compare ΔC_D very well
  - ΔC_D relative error between STAR-CCM+ and LAVA within 1.5%
- Decreasing drag with increase in cruise propeller thrust
  - At cruise power of 230.1 lbf of thrust, 52.6 drag count reduction



Results – Cruise Propellers
Wing Drag Coefficient

- Decreasing wing drag with increase in cruise propeller thrust
  - At cruise thrust of 230.1 lbf, 49.5 drag count reduction
- Much of drag reduction is due to decrease in pressure drag
  - 50.6 drag count decrease
- Viscous drag remains almost constant with increase in wingtip propeller thrust
  - 1.1 drag count increase



Conclusion

- Cruise propellers and high-lift system modeled and analyzed individually
  - Powered on results compared with powered off results
- High-lift Propellers
  - Increases lift and lift-curve-slope for power on configuration compared to power off
  - Increases $C_{L,max}$ as much as 65.4%
  - Gentler flow separation after $C_{L,max}$
- Cruise Propellers
  - Decreases drag with increase in thrust
  - Decrease in wing drag is due to reduction in pressure drag
  - At cruise thrust of 230.1 lbf, CFD predicts 52.6 drag count reduction with cruise propellers powered on