Aerodynamic Evaluation of the D8 "Double-Bubble" Aircraft Nacelle Design

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Outline

• The D8
  – Concept
  – Goals

• Modeling and Mesh Topology
  – Use Cart3D inviscid mesh adaptation to guide overset viscous mesh
  – O-mesh with wake boxes
  – Mesh sensitivity

• Clean Configuration
  – Comparison with experiment
  – Independent verification of D8 concepts

• Podded Nacelle
  – Geometry
  – Results
MIT D8 “Double-Bubble” Aircraft

- MIT team concept of N+3 advanced vehicle configuration
  - Lower fuel burn
  - Lower noise
  - Reduce emissions
- 180 passengers
- 3000 nmi range
- 118 ft span
- ~Boeing 737 size
MIT/Pratt & Whitney/Aurora D Series
Airframe & Propulsion Technology Overview

Novel configuration plus suite of airframe and propulsion technologies, and operations modifications

- Reduced Secondary Structure weight
- Active Load Alleviation
- Natural Laminar Flow on Wing Bottom
- Advanced Structural Materials
- High Bypass Ratio Engines (BPR 20) with High-Efficiency Small Cores
- Health and Usage Monitoring
- Lifting Body
- Faired Undercarriage
- LDI Advanced Combustor
- Advanced Engine Materials
- Boundary Layer Ingestion
- Distortion Tolerant Fans
- Tt4 Materials and advanced cooling
- Variable Area Nozzle
Fuselage Advantages

• “Double-bubble” fuselage provides more lift
  – Gives partial span-wise loading / smaller wing
• Shorter cabin (wider body)
  – Results in lighter landing gear support structure
• Provides a nose-up pitching moment
  – Shrinks horizontal tail
  – Lighter horizontal tail
Lower Cruise Speed

• M=0.72
  – Lower sweep wing
    • Reduced structural load => Lower weight
    • Increased CL
    • Can eliminate high-lift devices
  – Proper speed at engine fan face (M=0.6)
    • Reduces nacelle, inlet size

• Reduced nacelle drag
  – Nacelles embedded in the π-tail and fuselage
  – Reduced size, weight
Embedded Rear-Mounted Engines

• Boundary Layer Ingesting (BLI) engines for propulsive efficiency
  – Thicker boundary layer in the rear
  – Designed for M=0.6 flow around engine inlet area
  – Distortion tolerant fan
  – High bypass ratio (~20)

• Lower engine-out yaw
  – Reduced vertical tail size

• Noise shield

Fans like flow at ~ M=0.6
Wind Tunnel Tests

• Wright brothers wind tunnel at MIT
  – Low speed (100 and 120 mph) ≈ M=0.15
  – Clean configuration: α=0, 1.9, 4.4, 6.6, 8.8, 11, 13.3
  – Reₖ≈0.5 Million
  – 1:20 scale model
    • Tests complete
  – 1:11 scale model
    • Being constructed
      • w/, w/o empennage
    • Podded nacelle
    • Blended nacelle

The Mach and Re don’t match the flight, but the BLI effect is not expected to be very different

A. Uranga, MIT
Goals of This Work

• Independent assessment of the D8 design assumptions
  – Is the “double-bubble” fuselage advantageous?
    • Does it provide lift in the range of 10 to 20%?
    • Does it provide a nose-up pitching moment?
  – Boundary Layer Ingestion (BLI)
    • Quantify flow diffusion from fuselage geometry resulting in lower speed at the fan face

• Validate Overflow against the wind tunnel tests
  – Use best practices for nacelle assessment

• Assess nacelle performance using Overflow
  – Clean vs. Podded vs. Embedded
Simulations

• 120 mph (M=0.16)
• Alpha sweep: -2° to 14° in 2° increments
  – Half-body cases (symmetry assumed)
• Steady, turbulent flow
• Clean configuration
  – in Free-air
  – w/ WT
  – w/ WT+mount/fairing
• Podded
• Embedded (geometry, mesh generation in progress)
Outline

- The D8
- **Modeling and Mesh Topology**
  - Use Cart3D inviscid mesh adaptation to guide overset viscous mesh
  - O-mesh with wake boxes
  - Mesh sensitivity
- **Clean Configuration**
- **Podded Nacelle**
Cart3D/Aero Solution

Adaptive Mesh

- Component based inviscid solver
  - Automated mesh generation, complex geometries
- Adjoint-based adaptive mesh refinement used
  - Takes place of a lot of user time and expertise

Original, 70K
3 adapts, 400K
6 adapts, 7M
9 adapts, 30M
Overflow

• Overset mesh generation follows
  – Overset best practices
  – Guidance from Cart3D adaptive refinement

• Finite difference
  – Beam-Warming (approximate factorization/central difference)
  – Scalar dissipation

• Turbulence model (SA, SST) with target $y^+ \approx 1$
Wake Grid with O-Grid Topology

- Eliminate C- mesh
- Wake capture
- Tip vortex resolution
Volume Mesh

- 19 near-body grids
- 1 WT grid
- 4 wake grids
- 9 box grids
- 2 core grids
- 35 total grids
- Clean: ~80 Million Pts.
- Podded: ~87 Million Pts.

- Wake grids
- Body-fitted grids
- WT mesh
- Front WT core
- Rear WT core
- Box grids to cover test section
Mesh Sensitivity

• Test each parameter independently
  – Wall spacing ($y^+$)
  – Near-wall stretching ratio
  – Surface spacing
    • LE, TE, ...
  – Off-body spacing

• Study done at $\alpha=0^\circ$
  – SA turb. model
CL, CD Sensitivity to $y^+$

D8 with WT walls and Strut, $M=0.16$, $\alpha=0$  
$SR=1.15$, $DS_s=1$, $DS_o=0.15$
CL, CD Sensitivity to Surface Spacing

D8 with WT walls and Strut, M=0.16, α=0    y^+=1, SR=1.15, DS_o=0.15

Number of Points

40 M 60 M 80 M 100 M 120 M

%CL

0 5 10 15 20 25 30 35

%CD

0 0.024 0.028 0.032 0.036 0.04

ΔS_{surface}

CL

0 0.3 0.35 0.4 0.45

CD

0 0.024 0.028 0.032 0.036 0.04
**CL, CD Sensitivity to Stretching Ratio**

D8 with WT walls and Strut, $M=0.16$, $\alpha=0$  
$\gamma^+=1$, $D_{Ss}=1$, $D_{So}=0.15$

- **CL** graph
  - Stretching Ratio: 1.05 to 1.3
  - CL values: 0.4, 0.4, 0.4

- **CD** graph
  - Stretching Ratio: 1.05 to 1.3
  - CD values: 0.024, 0.028, 0.032

- **%CL** graph
  - Number of Points: 70 to 100 M
  - %CL values: 0, 0, 0

- **%CD** graph
  - Number of Points: 70 to 100 M
  - %CD values: 35, 25, 15
CL, CD Sensitivity to Off-Body Spacing

D8 with WT walls and Strut, M=0.16, \( \alpha=0 \)

\[ y^+=1, \ SR=1.15, \ DS_s=1 \]

The graphs show the sensitivity of lift coefficient (CL) and drag coefficient (CD) to off-body grid spacing. The graphs are labeled with the conditions under which the data were collected. The plots indicate a consistent trend for both CL and CD with varying grid spacing, suggesting minimal sensitivity to changes in spacing within the observed range.
Production Mesh

• Tested each parameter independently ($\alpha=0^\circ$, SA)
  – Wall-normal spacing (tested 0.5 to 5)
    • 0.00016 $\Rightarrow$ $y^+$ $\approx$ 1
  – Stretching ratio (tested 1.1 to 1.25)
    • 1.15
  – Surface spacing (tested LE spacing of 0.025 to 0.3%)
    • LE spacing $\approx$ 0.006 (0.1% chord)
    • TE spacing $\approx$ 0.003 (0.05% chord)
    • Inboard airfoil covered by $\sim$550 points
    • Outboard airfoil covered by $\sim$300 points
  – Off-body spacing (tested 0.1 to 0.3)
    • 0.15
Solution Consistency, Sensitivity

- Pegasus vs. Xrays vs. c3Lib
  - lift varies 2.9%, drag varies 1.1%
- AF vs. Diagonal vs. Roe vs. HLLC
  - lift varies 3%, drag varies 1.4%
- Low-Mach pre-conditioner
  - No change in lift and drag
- Unsteady algorithm
  - Flow remained steady with minor change in lift and drag
- Various WT Inlet/Exit Boundary Conditions
  - Minor variations in integrated forces
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• Podded Nacelle
Convergence and Solution

Residual History

Force/Moment History

Total Lift Coefficient

Total Drag Coefficient
$C_L$ Comparison

- WT
- Cart3D
- Overflow (SA)
- Overflow (SST)
$C_D$ Comparison

- WT
- Cart3D
- Overflow (SA)
- Overflow (SST)
Span-wise Loading

Fuselage provides span loading
Pi-tail has minimum negative loading
Component-wise Break-down

**CL**

- Total
- Fuselage
- Wing
- Pi-tail

**CD**

- Total
- Fuselage
- Wing
- Pi-tail

**Cm**

- Total
- Fuselage
- Wing
- Pi-tail

*Fuselage provides a pitch-up moment*
Boundary Layer Ingestion

Cruise condition, $\alpha=4^\circ$
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Podded Nacelle

• In free-stream
  – Under-wing
  – Between π-tail
  – Side-mount

• Nacelle/Hub/Pylon
  – 7 additional grids
    • One for each component
    • Two collar grids
      – Fuselage/pylon, nacelle/pylon
    • Two caps for the hub
      – nose, base
Podded Nacelle
Podded Nacelle

- Flow-through nacelle
- CL, CD increments w/rt clean configuration
  - Lower CL
  - Higher CD
- Compare w/ embedded
- Engine model
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Conclusions

• CFD predictions validate basic ideas behind D8
  – Fuselage carries ~15% of the lift at cruise
  – Fuselage provides a positive pitching moment at cruise
  – Rear of the fuselage acts as diffuser

• CL, CD compare well to the experiment
  – Better agreement with SST

• Podded: Results in increased drag, reduced lift as expected
Future Work

• Placement of Podded Nacelles

• Blended Nacelles
  – Original configuration
    • Three-engine
  – Present concept
    • Two-engine
  – Geometry, mesh, CL, CD increments
    • CGT
      • Blender Sub-D surfaces for C-2 continuity?

• Fan model (pressure disk, rotating blades?)
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