Aerodynamic Design of Integrated Propulsion- Airframe Configuration of the Hybrid Wing- Body Aircraft

May-Fun Liou[†], Hyoungjin Kim[*], BJ Lee[**] and Meng-Sing Liou[†]

[†] NASA Glenn Research Center

[*] *SAIC &* [**]*Vantage Partners, LLC,*

Cleveland, OH

AIAA Aviation 2017

June 5-9, 2017, Denver, Co.

Outline

- Background & Objectives
- Aerodynamics of Hybrid Wingbody-Propulsion System
- Technical Backgrounds
  - Geometric Parameterization
  - Mesh generation & deformation
- Optimization: Aero Performance & Constraints
- Analysis of Optimal Design
- Viscous Effects on Aerodynamic Performance
- Conclusion

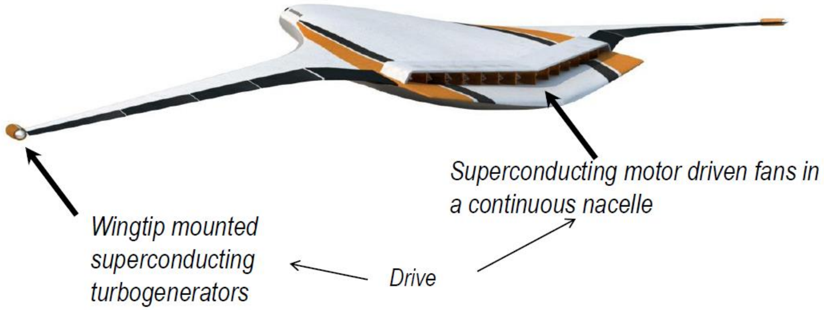
Background – Far Term (beyond 2035)

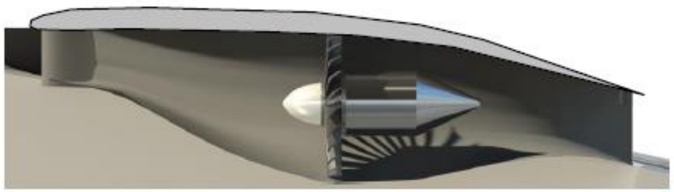
- HWB (hybrid wingbody) configuration requirements

TECHNOLOGY BENEFITS	TECHNOLOGY GENERATIONS (Technology Readiness Level = 5-6)		
	Near Term 2015-2025	**Mid Term** 2025-2035	**Far Term** beyond 2035
Noise (cum below Stage 4)	22 – 32 dB	32 – 42 dB	42 – 52 dB
LTO No_x Emissions (below CAEP 6)	70 – 75%	80%	>80%
Cruise No_x Emissions (rel. to 2005 best in class)	65 – 70%	80%	>80%
Aircraft Fuel/Energy Consumption (rel. to 2005 best in class)	40 – 50%	50 – 60%	60 – 80%

Distributed Electric Propulsion System

- Turboelectric Distributed Propulsion (TeDP)
  - Mail-slot nacelle near trailing edge
  - Boundary Layer Ingestion into embedded propulsor fans
  - Propulsor fans driven by superconducting electric motors
  - Wingtip mounted superconducting turbo-generators





Propulsor and inlet-nozzle systems

Felder, J., Kim, H. D., Brown, G. V., and Chu, J., "An Examination of the Effects of Boundary Layer Ingestion on Turboelectric Distributed Propulsion Systems," AIAA–2011–0300

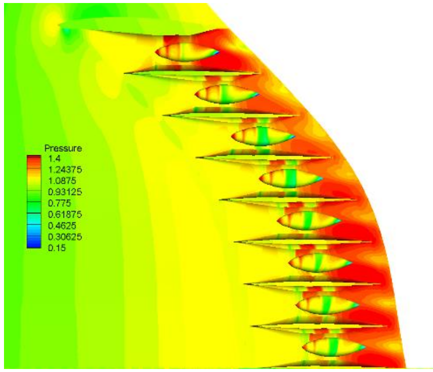
Development of Technologies for Hybrid Wing/body with Distributed Electric Propulsion

<table>
<tr><th></th><th>-2013</th><th>2014</th><th>2015</th><th>2016</th><th>2017</th></tr>
<tr><td>PAI Configurations</td><td>N3-X conceptual design*
N+2B inlet shape optimization</td><td colspan="2">N3-X with mailslot nacelle</td><td>N3X-Dep300 clean wing, 300 passenger cabin**</td><td>N3X-Dep300 with nacelle (PAI)</td></tr>
<tr><td>Inlet</td><td>inlet A – BLI wall shaping
crosswind analysis</td><td colspan="2">mailslot</td><td>mailslot nacelle cowl surface design</td><td>mailslot wall shaping</td></tr>
<tr><td>Propulsor</td><td>sizing/conceptual</td><td colspan="3">GE R4 scaled single stage fan,
conceptual study of counter rotating fan</td><td>electric fan design</td></tr>
<tr><td rowspan="2">Mesh</td><td colspan="2">unstructured iso – spring analogy</td><td colspan="3" rowspan="2">unstructured aniso mesh
crosschecked with overflow</td></tr>
<tr><td colspan="2">overset</td></tr>
<tr><td>Parameterization</td><td colspan="2">NURBS</td><td colspan="2">CST/ planform/inlet/nacelle</td><td>NURBS</td></tr>
<tr><td>CFD Modeling</td><td colspan="2">Roe/AUSM+UP
SA/2-eqs. turbulence models
LUSGS & GMRES</td><td colspan="2">N3X-Analysis with body-force model</td><td>drag decomposition
trim modeling</td></tr>
<tr><td>Optimization Method</td><td colspan="4">GBOM based on adjoint approach</td><td>adjoint/NSGA-II</td></tr>
</table>

Completed Current On-going & future works

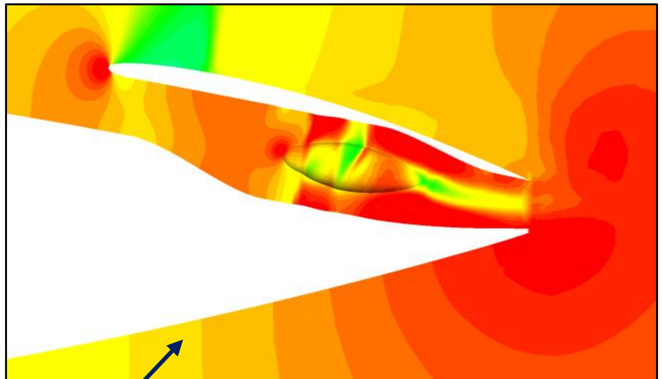
*Jim Felder et al. AIAA–2011–0300
**Craig L. Nickol AIAA-2012-0337

CFD flow-field of N3-X with Fan Propulsor

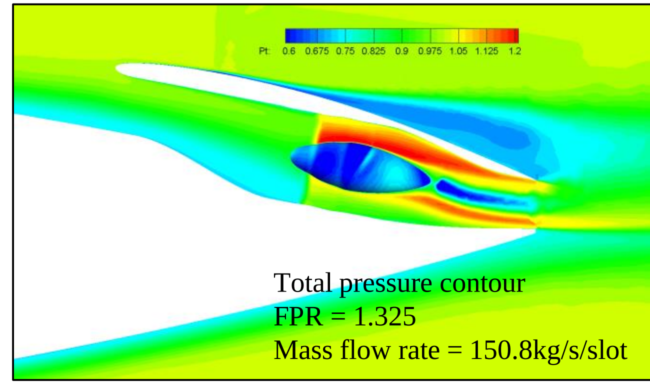


Static pressure contour
Mailslot top view

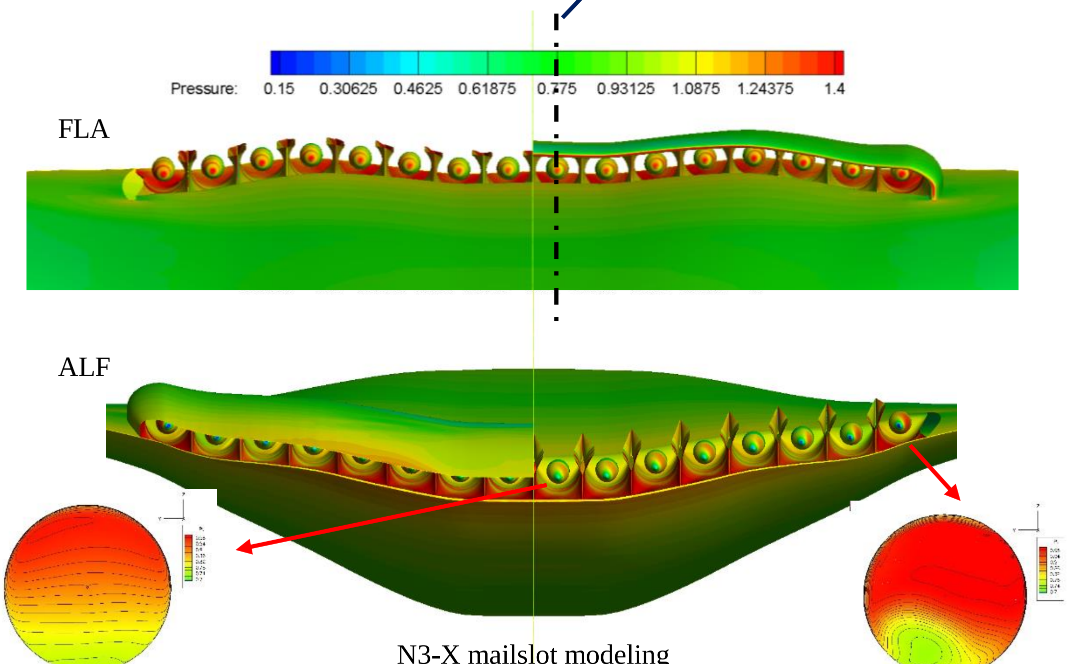
Flow field in the 1st slot with fan bodyforce model (2014)



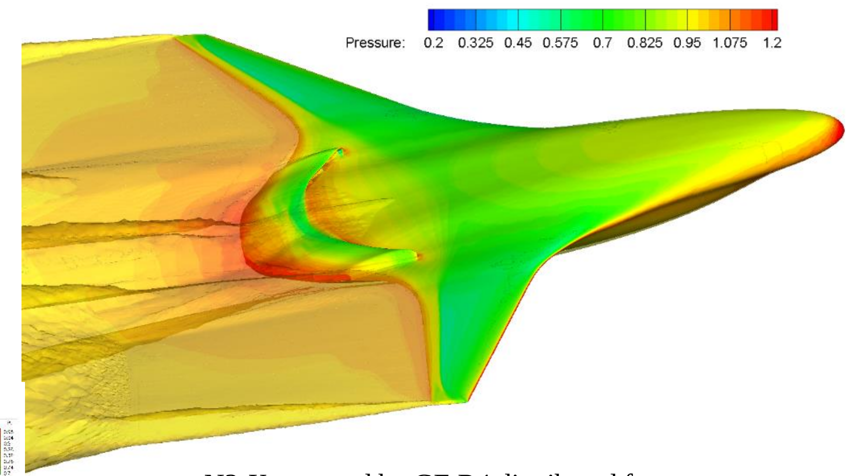
Static pressure contour



Total pressure contour
FPR = 1.325
Mass flow rate = 150.8kg/s/slot



N3-X mailslot modeling



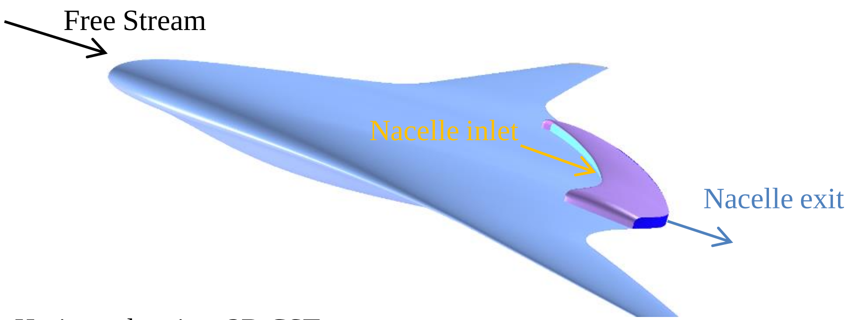
N3-X powered by GE R4 distributed fan
Kim et al. ISABE-2015-20228

Objective of the Present Work

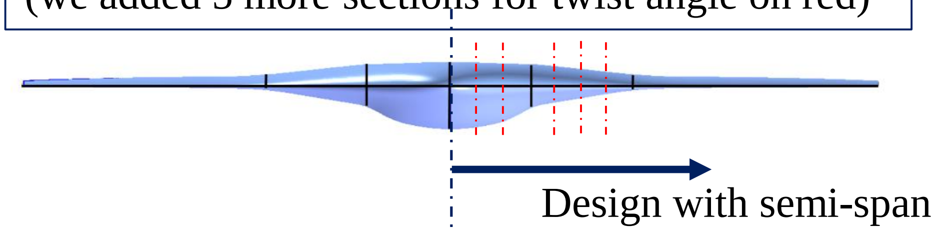
- Further refine parameterization strategy for general complex integrated propulsion-airframe system.
- Aerodynamic design under static stability constraints.
- Analysis and understanding of simulated flow-field of the optimized configuration

Parameterization of Wing and Nacelle

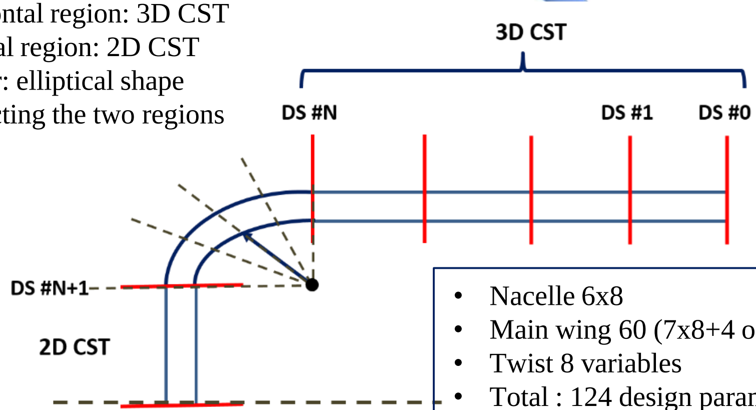
PAI configuration for present work



Design sections of surface design and twist angles (we added 5 more sections for twist angle on red)

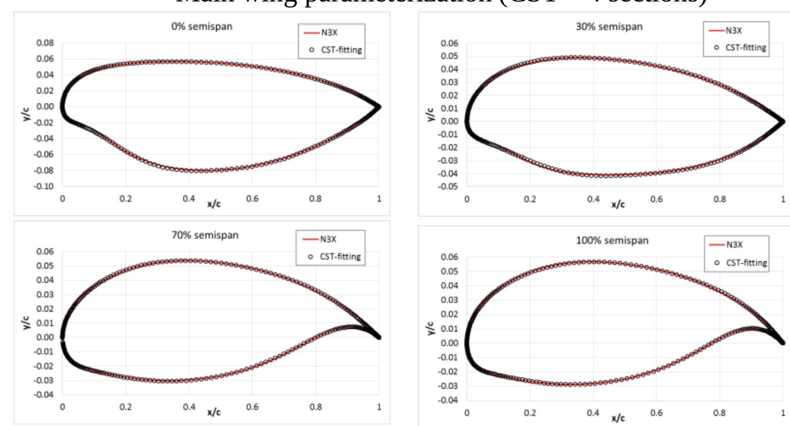


- Horizontal region: 3D CST
- Vertical region: 2D CST
- Corner: elliptical shape connecting the two regions

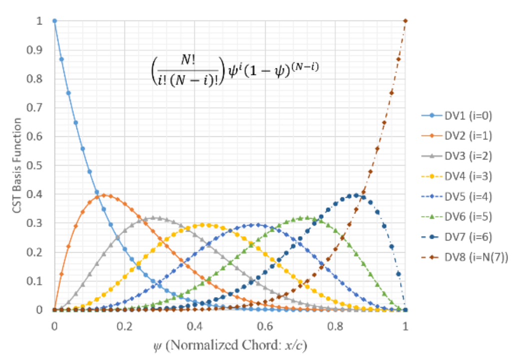


- Nacelle 6x8
- Main wing 60 (7x8+4 offset)
- Twist 8 variables
- Total : 124 design parameters

Main wing parameterization (CST – 4 sections)



Note: additionally, tip twist angle is used for trim constraint and smooth spanwise interpolation between design sections, thickness constraint for cabin space are applied.

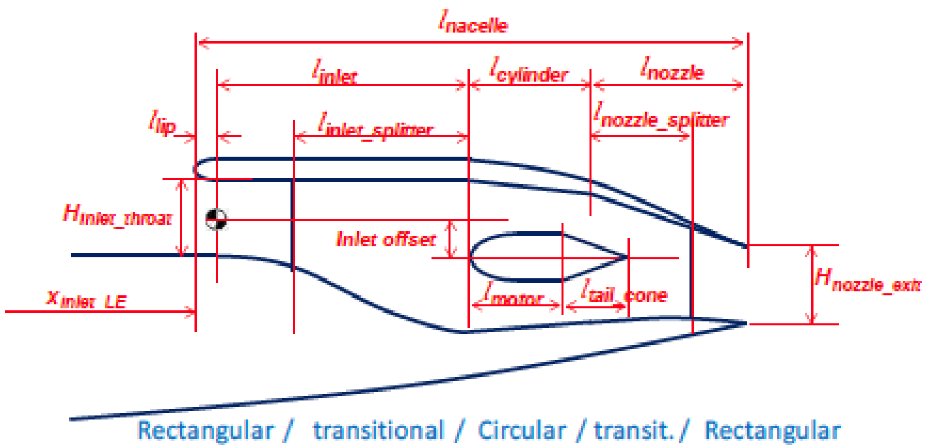


Section surface parameterization (CST)

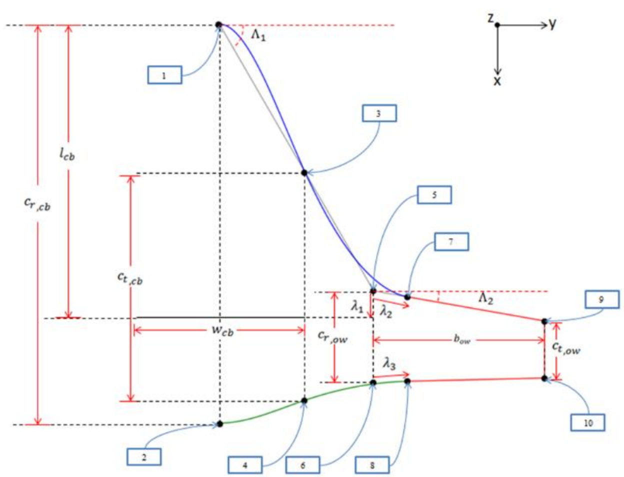
- 8 parameters for each of upper & lower surfaces
- Minimization of L2 norm
- CST basis function (RHS)
- Kulfan, B.,"Universal Parametric Geometry Representation Method," JA vol.45, No.1, 2008

Parameterization of Airframe and Inlet

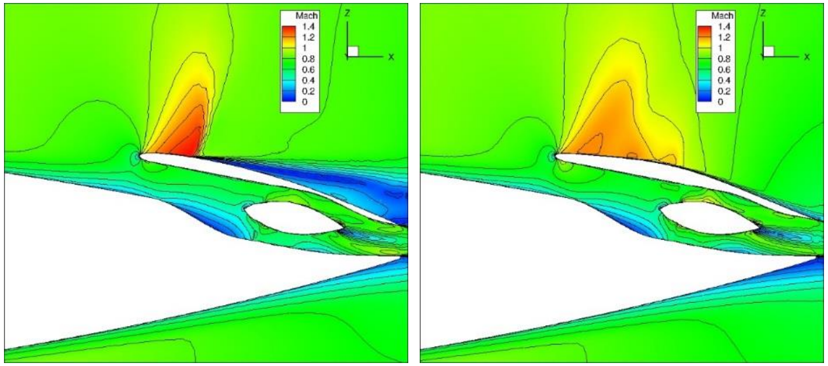
Inlet parameterization



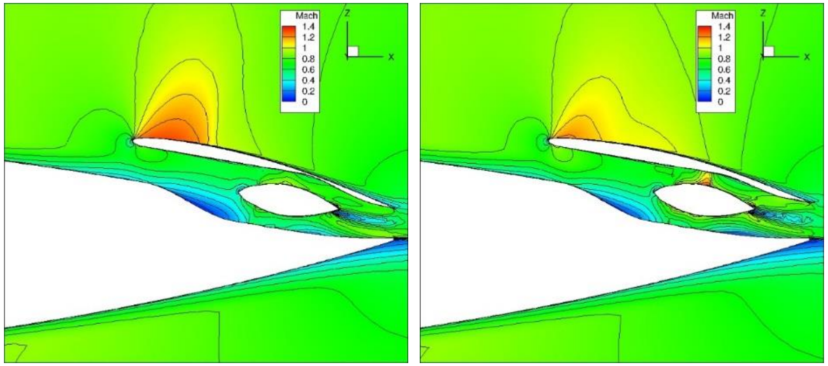
Planform parameterization



Example of aerodynamic shape optimization of nacelle



Passage 1



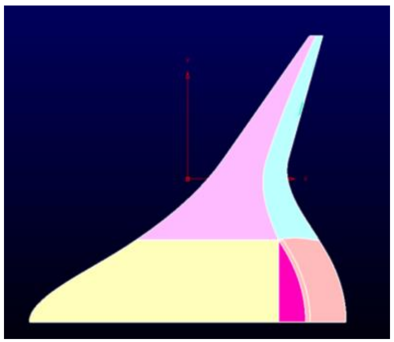
Passage 4

N3-X cowl shape design results:
Comparison of sectional local Mach contours, Left: initial, Right: design.
(Kim et al. AIAA 2015-3805)

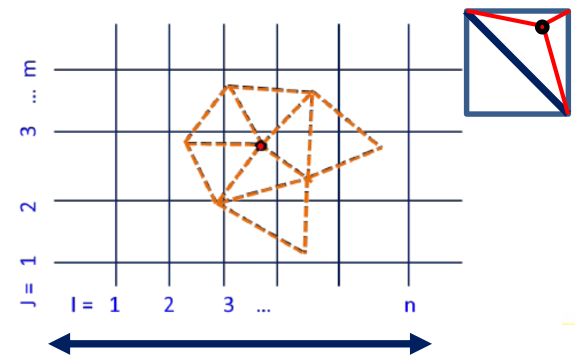
Note: Theses inlet/nozzle and planform parameters are not used in the present work, it is used for previous design for the current baseline model and will be refined in the future study.

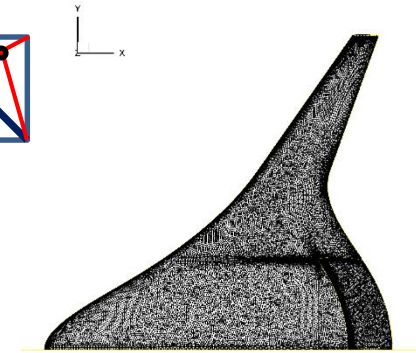
Mesh Generation & Deformation

- Mapping unstructured surface meshes on structured p3d (output of PAI configuration generator)
- Spring analogy from surface mesh deformation to volume mesh deformation

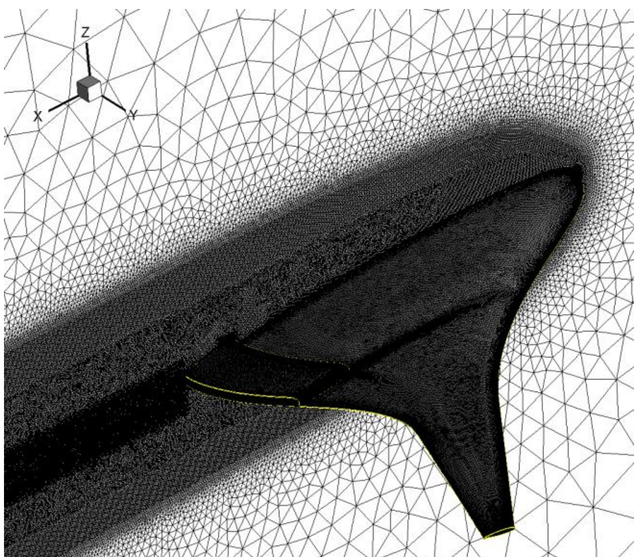


Baseline surface geometry (P3D)

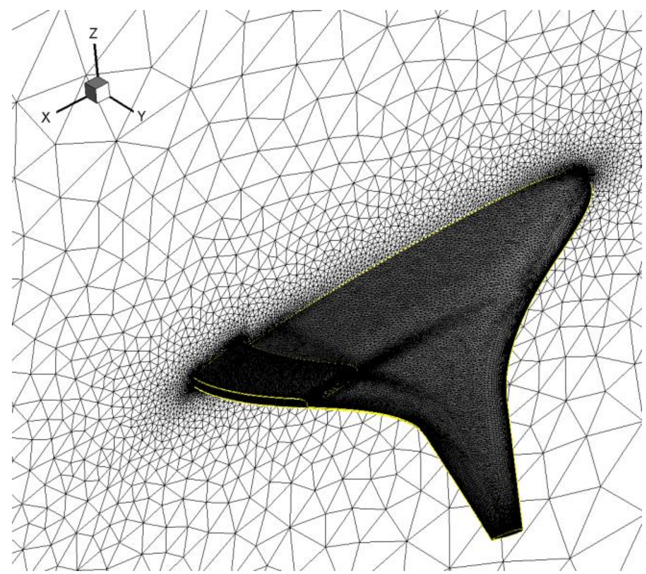




Baseline surface mesh



Mesh for RANS analysis



Mesh for inviscid flow analysis

Longitudinal trim & static stability

Trim : $\sum F_x = 0; \sum M_{cg} = 0 \; i.e. Drag = Thrust \;\; \& \, Pitching \; moment \; at \; c.g. is \; zero.$

Federal Aviation Regulations (FAR), Section 161 of PAR 23: *The airplane must maintain longitudinal trim under each of the following conditions: (1) A climb, (2) Level flight at all speeds, (3) A descent, (4) Approach.*

Static margin: Pitching moment arm - Distance between Xc.g. and the Xa.c.;

Mathematical expression - $K_n = -\frac{C_{M_\alpha}}{C_{L_\alpha}}$

Static stability: pitching moment changes caused by the perturbation in AOA revert the aircraft back into trim, i.e. $C_{M_\alpha} < 0$ ⟹ $K_n > 0$

Optimization : Aero Performance & Constraints

Minimize: C_D

Subject to: $C_L = C_{L_T}$, $C_M = C_{M_T} = 0$, *Specified SM (baseline 4%MAC)*

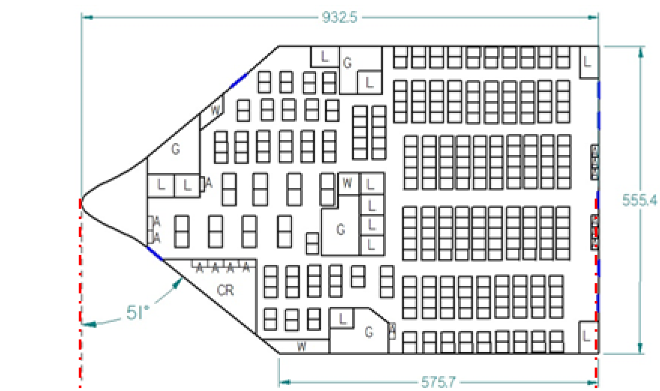
$R_{LE,nacelle} \geq R_{LE,baseline\ nacelle}$

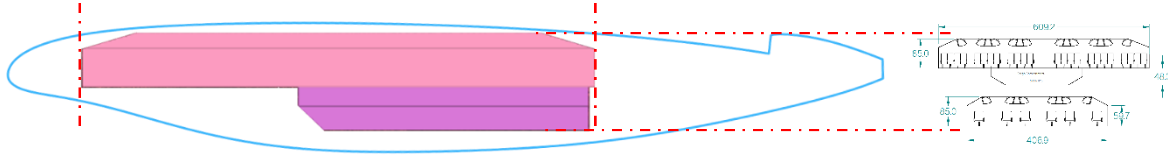
$(t/c)_{max} \geq (t/c)_{max,baseline}$ *for each design section*

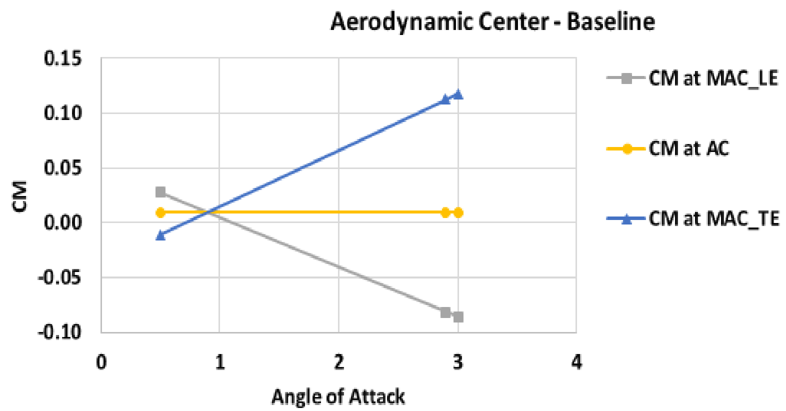
Minimize: $C_D = C_{D_0} + C_{D_\alpha}\Delta\alpha + C_{D_\theta}\Delta\theta_{wt}$

$$\begin{pmatrix} \Delta C_L \\ \Delta C_M \end{pmatrix} = \begin{pmatrix} C_{L_\alpha} & C_{L_\theta} \\ C_{M_\alpha} & C_{M_\theta} \end{pmatrix} \begin{pmatrix} \Delta\alpha \\ \Delta\theta_{wt} \end{pmatrix}, \quad \begin{pmatrix} \Delta\alpha \\ \Delta\theta_{wt} \end{pmatrix} = \begin{pmatrix} C_{L_\alpha} & C_{L_\theta} \\ C_{M_\alpha} & C_{M_\theta} \end{pmatrix}^{-1} \begin{pmatrix} \Delta C_L \\ \Delta C_M \end{pmatrix}$$

Cabin (301 Passengers) layout for thickness constraint

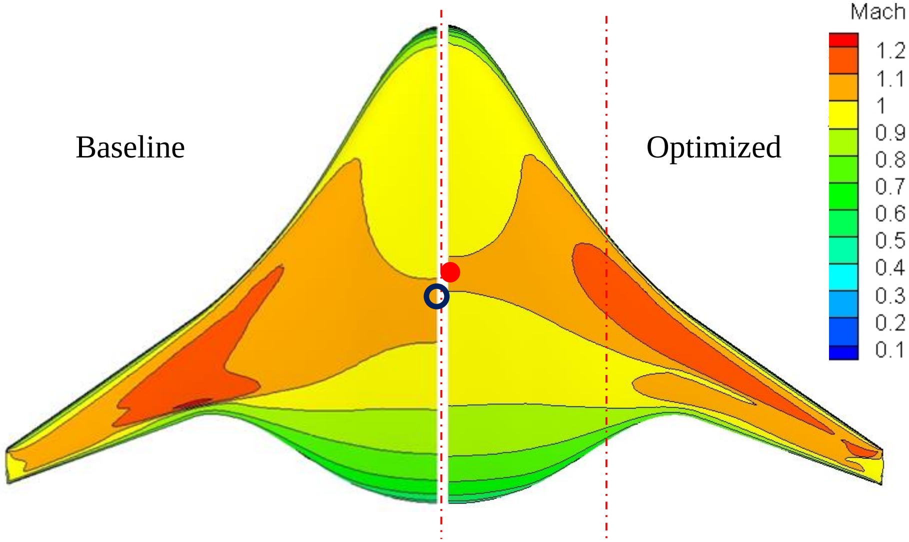




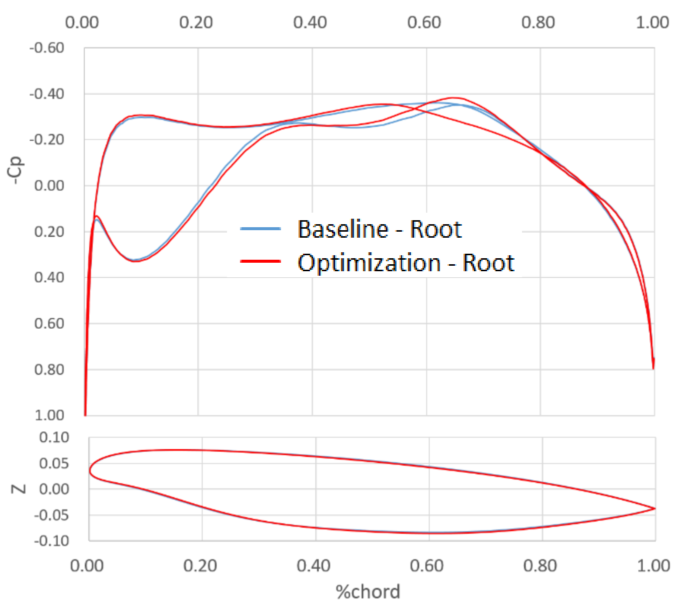


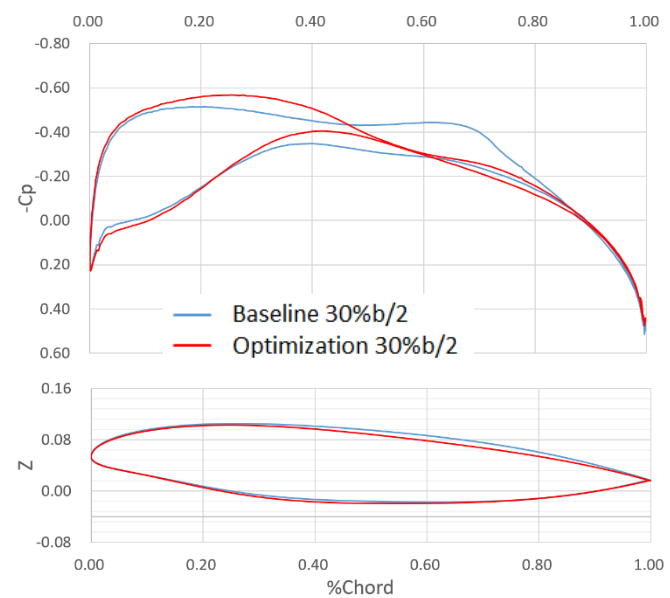
Craig L. Nickol AIAA-2012-0337

Clean-wing Design

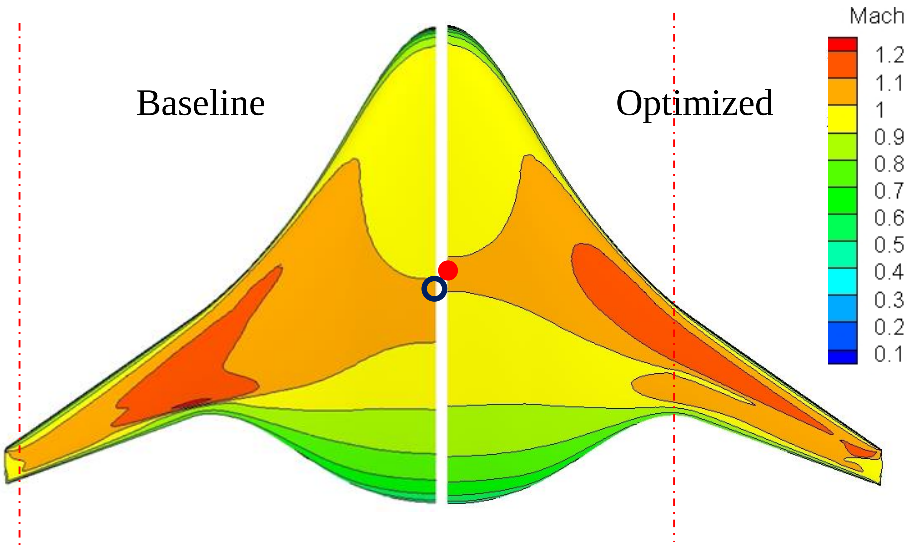


- Front loaded optimized wing
- X_{CG} moved from 38.21%c (○) to upstream (36.73%c●)
- SM=9%MAC
- Shock strength at TE is reduced





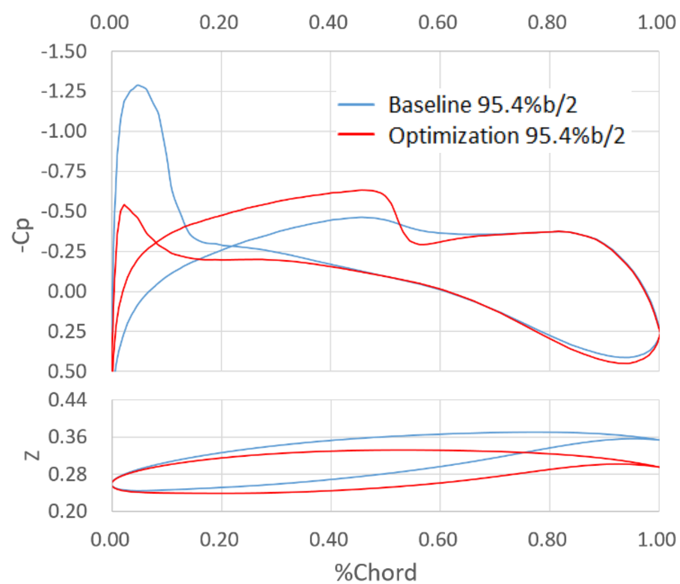
Clean-wing Design

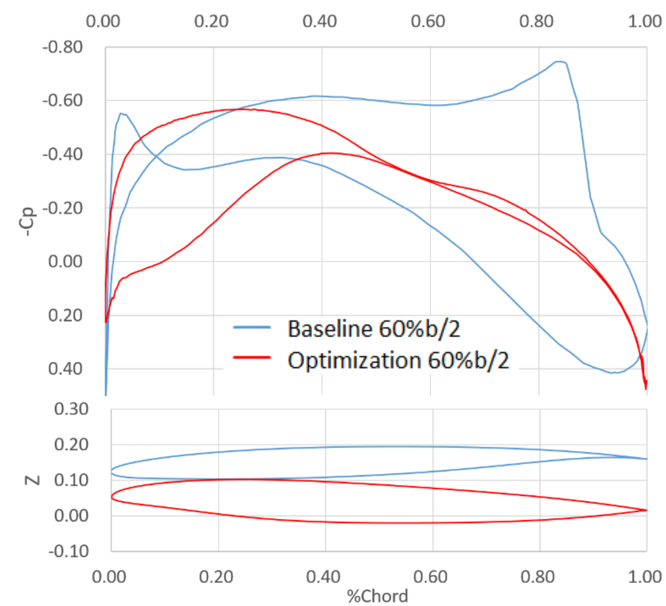


- Baseline (26.3cnts) :
  (Induced drag): (wave drag)
  =87%:13%
- 15% (-3.4 cnts) induced drag reduction
- 85% (-2.9 cnts) wave drag reduction

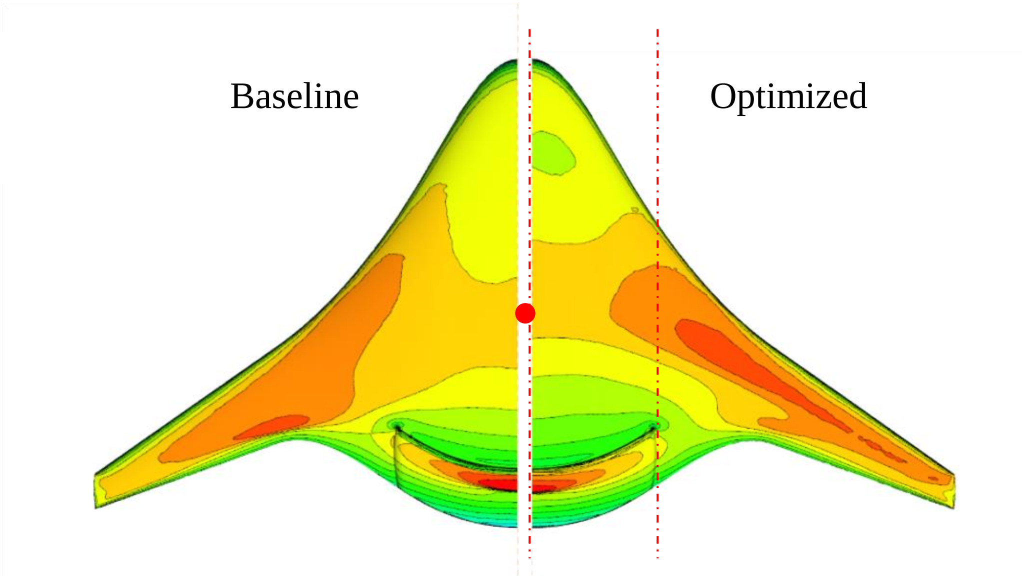
	C_{Di}	C_{Dw}	$C_{Di}+C_{Dw}$
Baseline	87.24%	12.76%	100.00%
Optimized	74.36%	1.87%	76.23%
delta	-12.88%	-10.89%	-23.77%

-6.3 counts

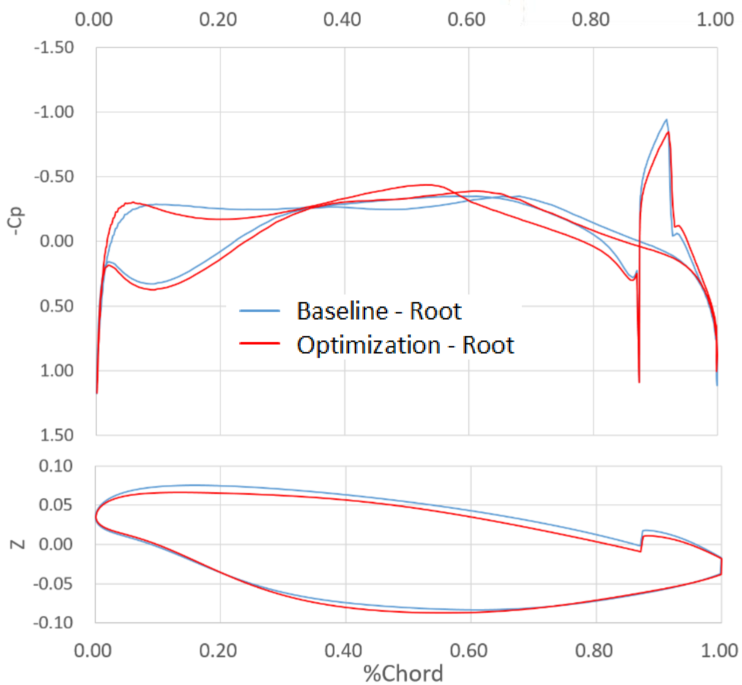


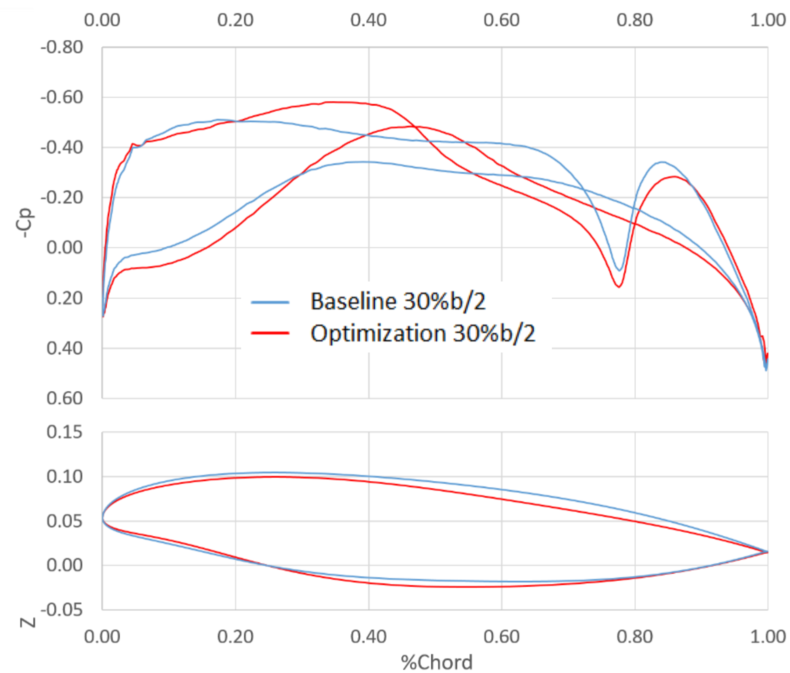


Propulsion Airframe Integration Design

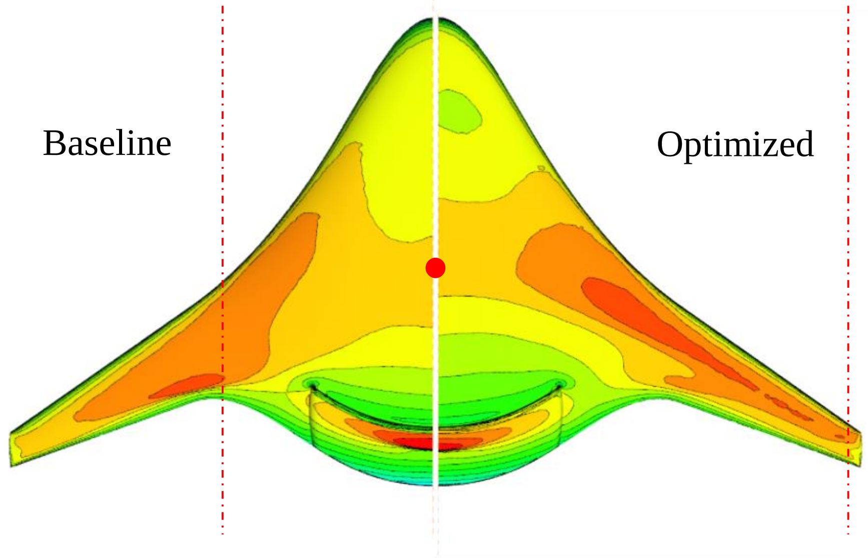


- Baseline (43cnts) :
  (Induced drag): (wave drag) =93%:7%
- SM=4%MAC
- X_{CG} almost not changed even though the center of pressure changed significantly at outboard.
- Nacelle and inboard area dominate the longitudinal stability.





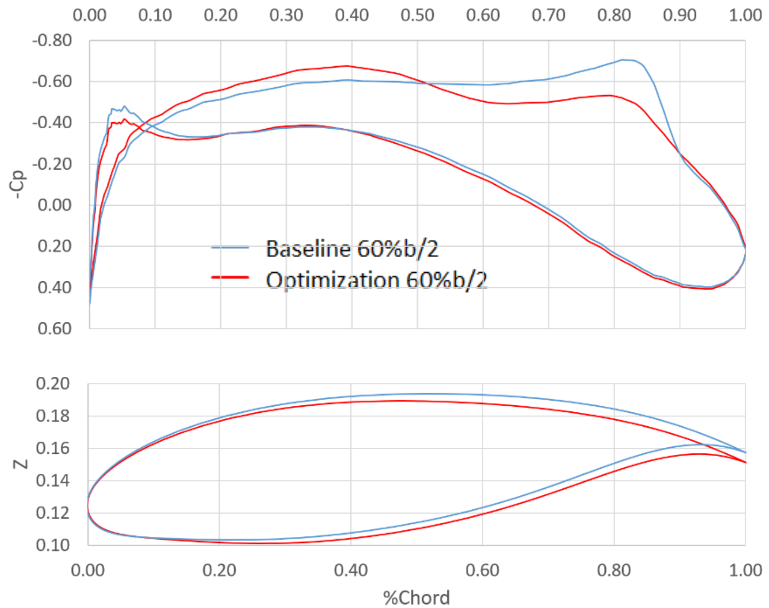
Propulsion Airframe Integration Design

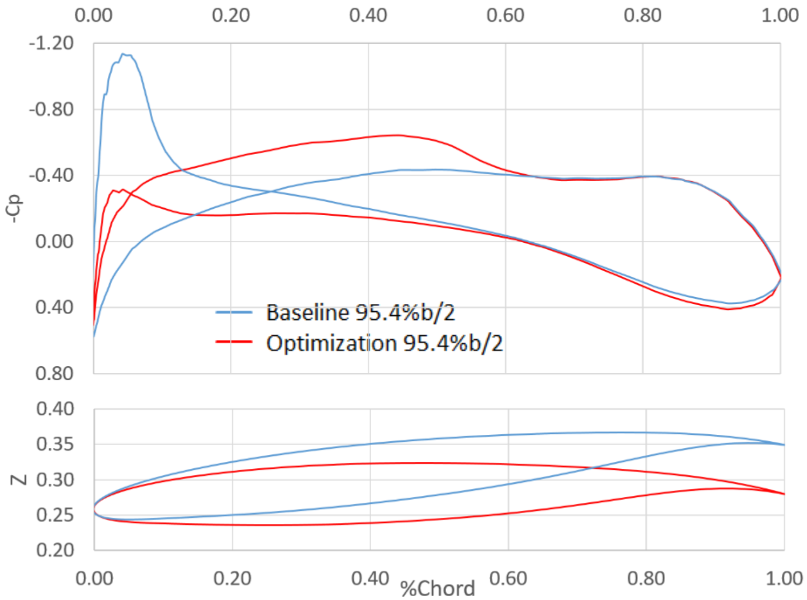


- Baseline (43cnts) : (Induced drag): (wave drag) =93%:7%
- 19% (-7.5cnts) induced drag reduction
- 75% (-2.1cnts) wave drag reduction

	C_{Di}	C_{Dw}	$C_{Di}+C_{Dw}$
Baseline	93.47%	6.53%	100.00%
Optimized	75.75%	1.64%	77.39%
Delta	-17.72%	-4.89%	-22.61%

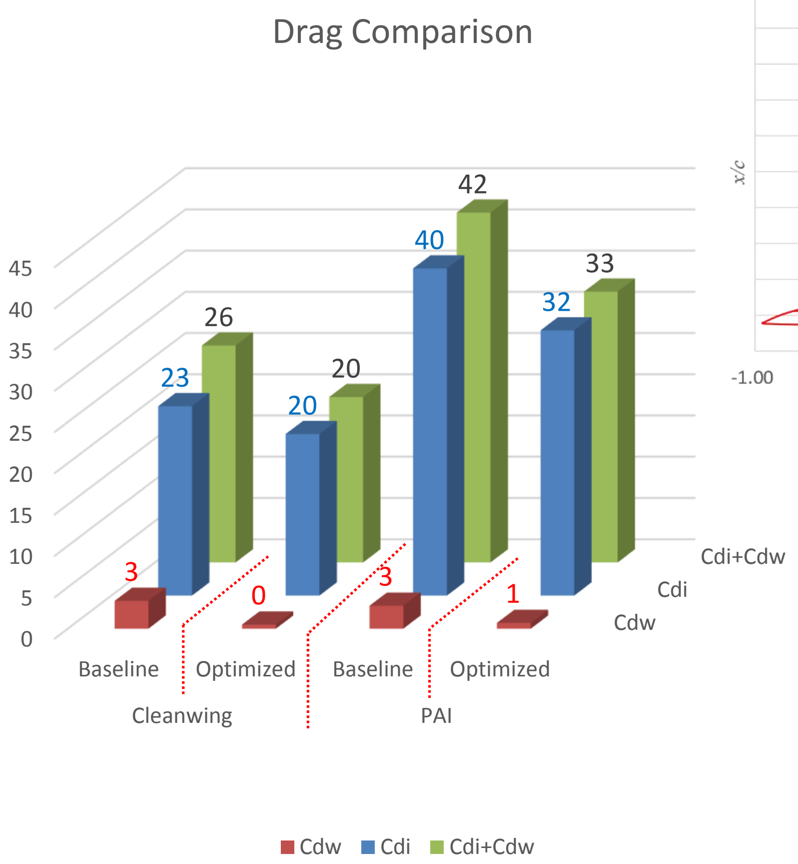
-9.59 counts

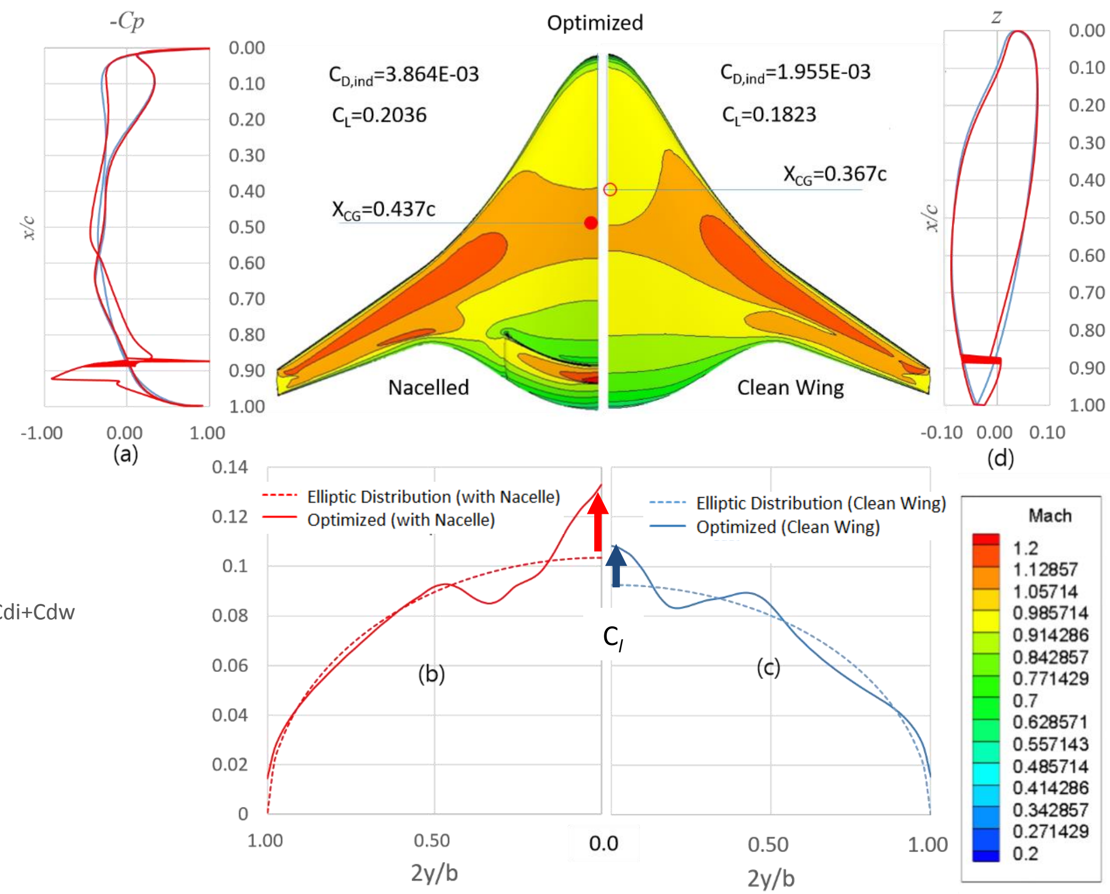




Clean-wing vs PAI

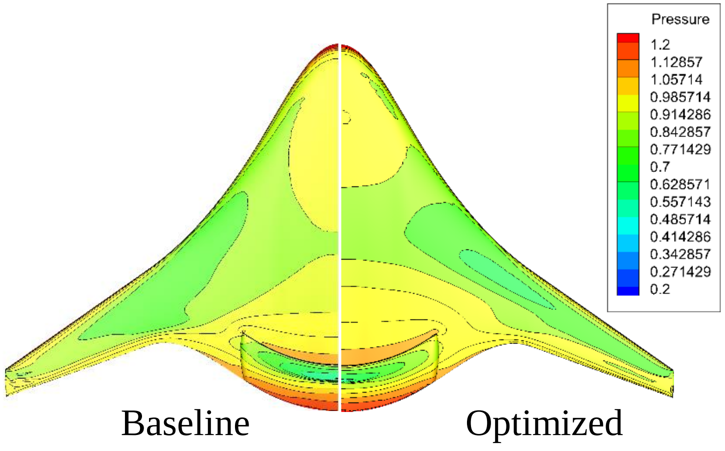
- Lift contribution of nacelle affects longitudinal stability at inboard area.
  - PAI baseline - 12% more lift, 35~39% more drag (vs. Cleanwing baseline)
  - X_{CG} is predicted further downstream around 43.7%c while clean wing has CG at 36.7%c.
- More induced drag dominant design.



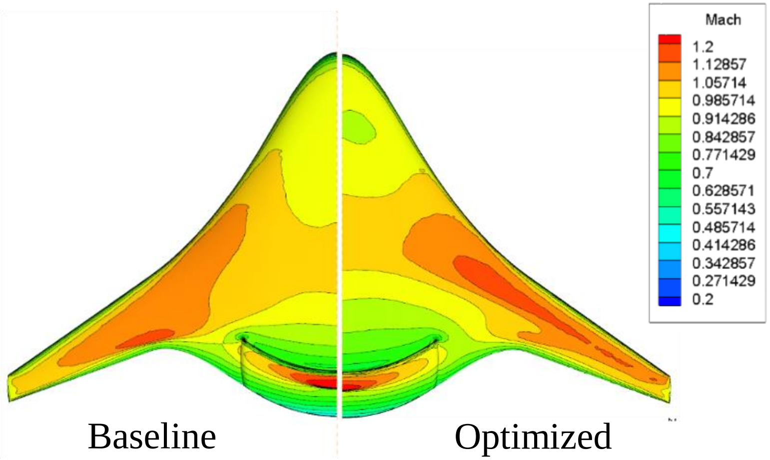


Viscous Effects on Aerodynamic Performance

- Inviscid analysis is used for fast design optimization.
- RANS analysis for optimized PAI configurations.



RANS analysis – Ps Contour



Euler Analysis – Mach Contour

RANS	C_L	C_{Di}	C_{Dw}	C_{Dv}	$C_{Di}+C_{Dw}+C_{Dv}$
Baseline	0.1503	35.7	3.85	57.5	97.1
Optimized	0.1520	22.9	0.70	56.6	80.5
Delta	+0.0017	-12.8	-2.89	-0.92	-16.6
Delta%	+1.3%	-35.86%	-74.96%	-1.59%	-17.10%

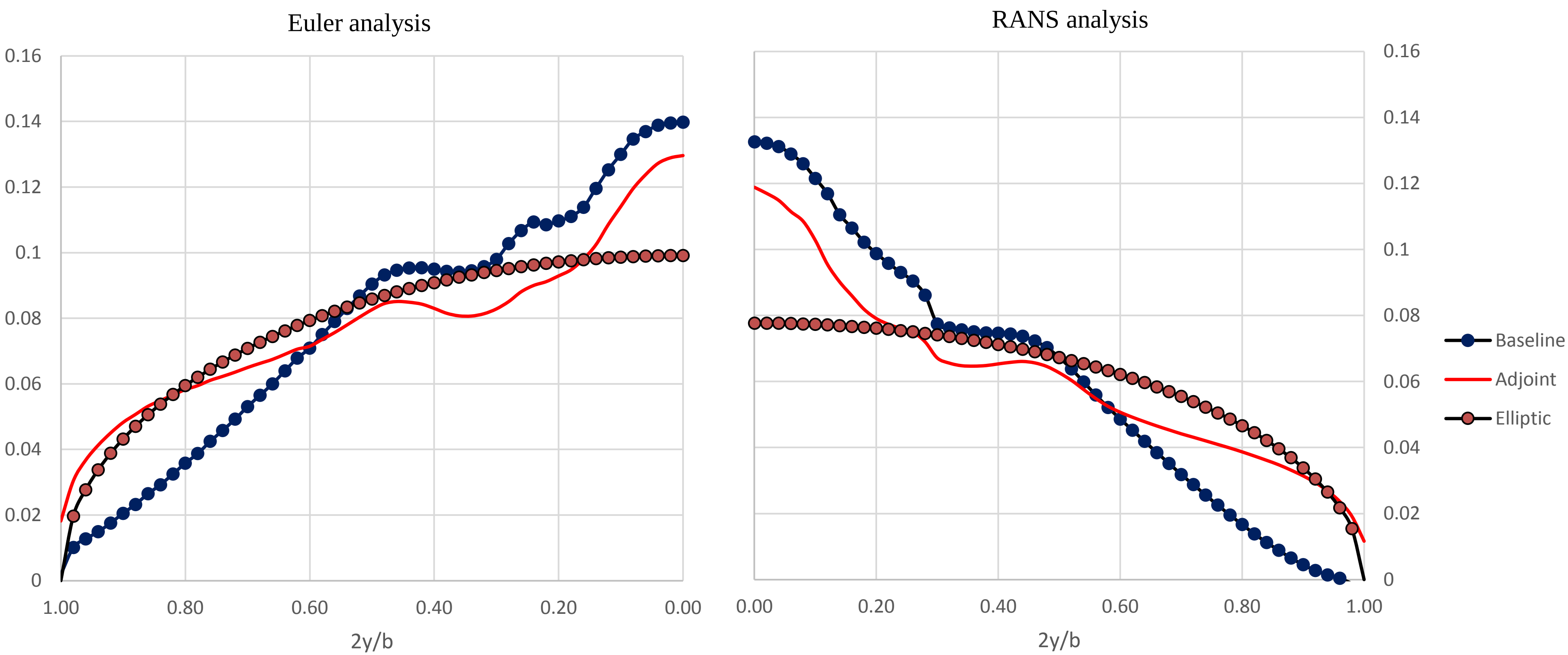
Euler	C_L	C_{Di}	C_{Dw}	$C_{Di}+C_{Dw}$
Baseline	0.1934	39.64	2.77	42.41
Optimized	0.1934	32.12	0.70	32.82
Delta	0.00	-7.52	-2.07	-9.59
Delta%	0%	-18.96%	-74.88%	-22.6%

RANS	C_{Dw}-cowl
Baseline	1.96
Optimized	0.78
Delta	-1.19
Delta%	-60.49%

Euler	C_{Dw}-cowl
Baseline	1.29
Optimized	0.53
Delta	-0.76
Delta%	-58.72%

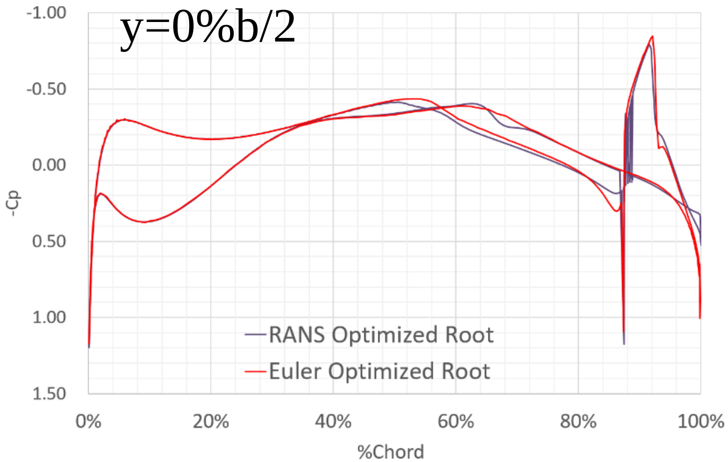
Viscous Effects on Aerodynamic Performance-cont’d

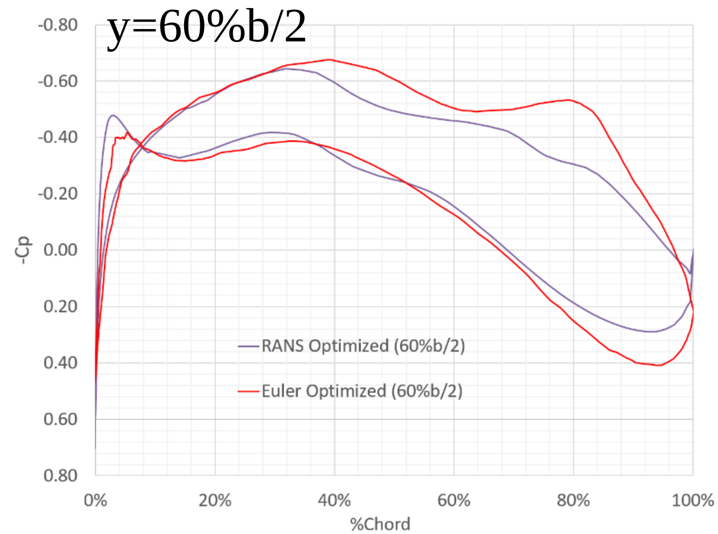
- Span-wise Lift Distribution

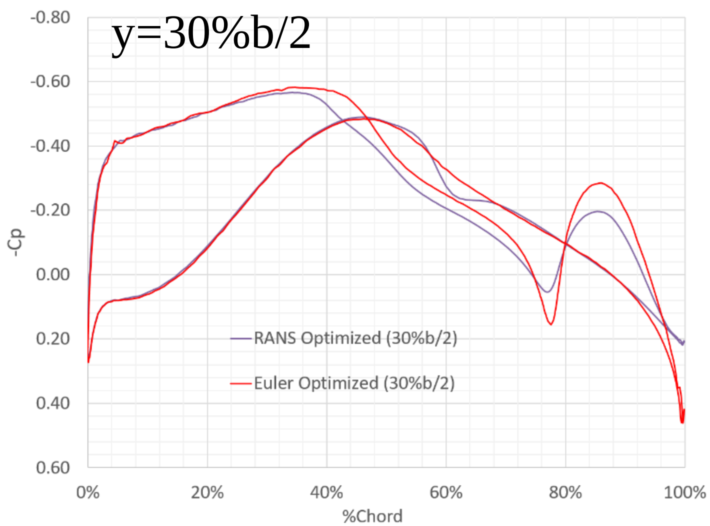


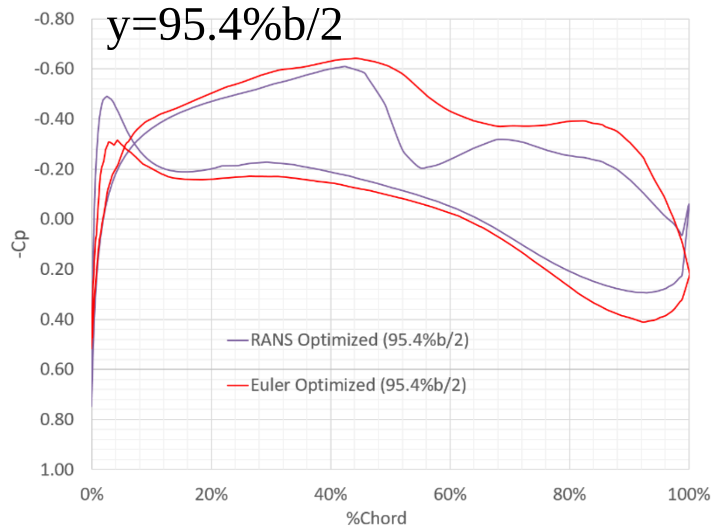
Viscous Effects on Aerodynamic Performance-cont'd

- Surface Pressure Distribution









Conclusion

- A design analysis tool for efficient geometry generation and optimal shape design of the hybrid wing body propulsion airframe integration (PAI) has been developed

- Preliminary PAI configurations of HWB are designed with Euler analysis for fast turn around and rigorously investigated with RANS analysis.
  - The RANS analysis results carries the improvement of performance consistently as Euler analysis predicted.

- Aerodynamic optimization with lift, pitching moment constraints was conducted ; the first trim, longitudinal stability consideration for HWB PAI configuration
  - Almost 10 counts of drag reduction could be achieved.
  - Design starting from PAI concept is required due to that nacelle installation has significant impact on aerodynamics, trim and longitudinal stability.

Future Works

<table>
<tr><th></th><th>-2013</th><th>2014</th><th>2015</th><th>2016</th><th>2017</th><th>2018-</th></tr>
<tr><td>PAI Configurations</td><td>N3-X conceptual design*
N+2B inlet shape optimization</td><td colspan="2">N3-X with mailslot nacelle</td><td>N3X-Dep300 clean wing, 300 passenger cabin**</td><td>N3X-Dep300 with nacelle (PAI)</td><td>N3X-Dep300 with nacelle and propulsor</td></tr>
<tr><td>Inlet</td><td>inlet A – BLI wall shaping
crosswind analysis</td><td colspan="2">mailslot</td><td>mailslot nacelle cowl surface design</td><td>mailslot wall shaping</td><td>propulsion system sizing with fan/nozzle</td></tr>
<tr><td>Propulsor</td><td>sizing/conceptual</td><td colspan="3">GE R4 scaled single stage fan,
conceptual study of counter rotating fan</td><td>electric fan design</td><td>BLI tolerant fan</td></tr>
<tr><td rowspan="2">Mesh</td><td colspan="2">unstructured iso – spring analogy</td><td colspan="3" rowspan="2">unstructured aniso mesh
crosschecked with overflow</td><td rowspan="2">unstructured – airframe/inlet/nozzle
structured - propulsor</td></tr>
<tr><td colspan="2">overset</td></tr>
<tr><td>Parameterization</td><td colspan="2">NURBS</td><td colspan="2">CST/ planform/inlet/nacelle</td><td>NURBS</td><td>fan blade parameterization (CST)</td></tr>
<tr><td>CFD Modeling</td><td colspan="2">Roe/AUSM+UP
SA/2-eqs. turbulence models
LUSGS & GMRES</td><td colspan="2">N3X-Analysis with body-force model</td><td>drag decomposition
trim modeling</td><td>through flow model – axi-symmetric (CSTALL)
multi-stage CFD (SWIFT)</td></tr>
<tr><td>Optimization Method</td><td colspan="4">GBOM based on adjoint approach</td><td>adjoint/NSGA-II</td><td>adjoint/NSGA-II</td></tr>
</table>

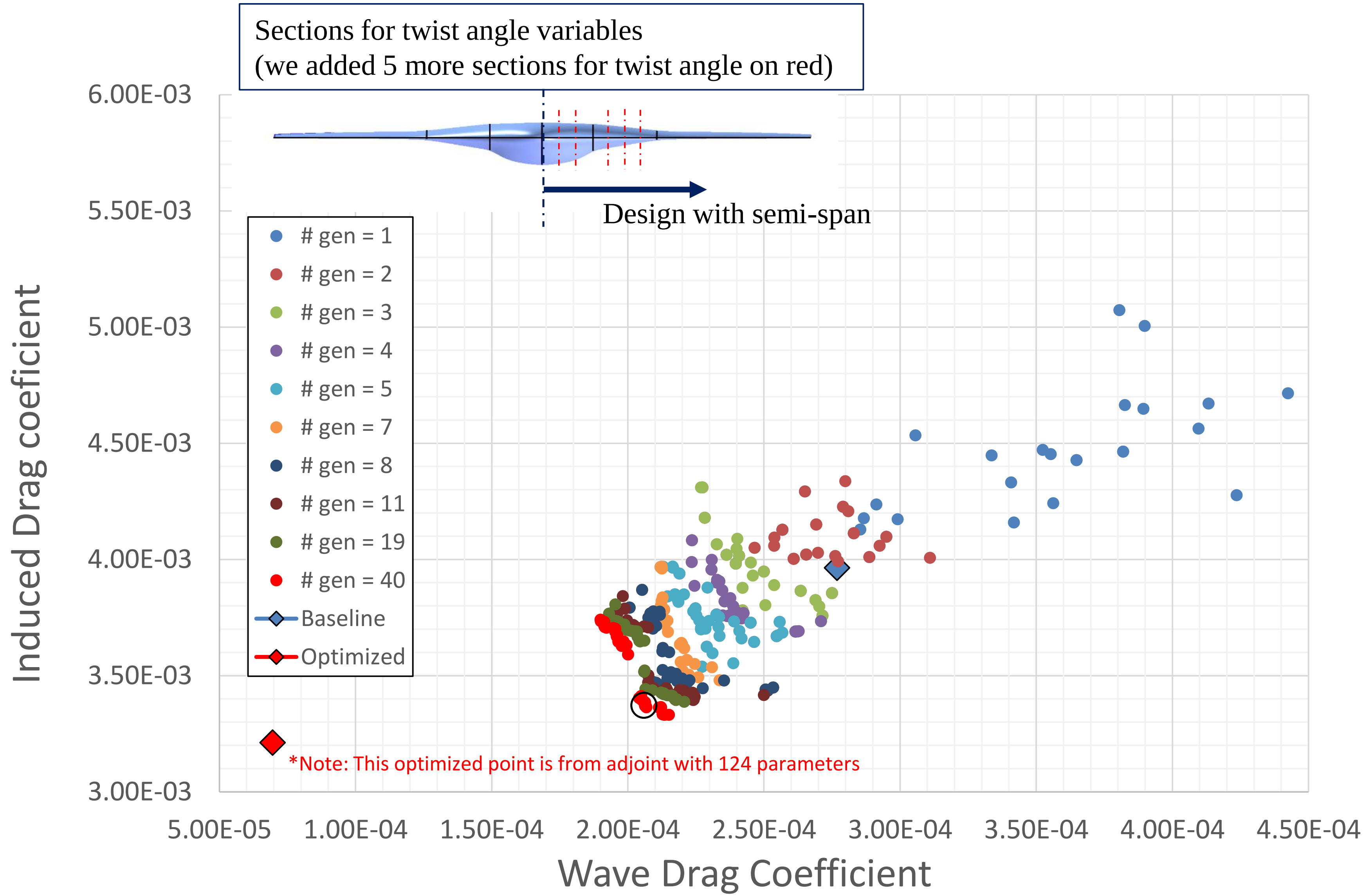
Completed (blue) | Current (orange) | On-going & future works (green)

*Jim Felder et al. AIAA–2011–0300
**Craig L. Nickol AIAA-2012-0337

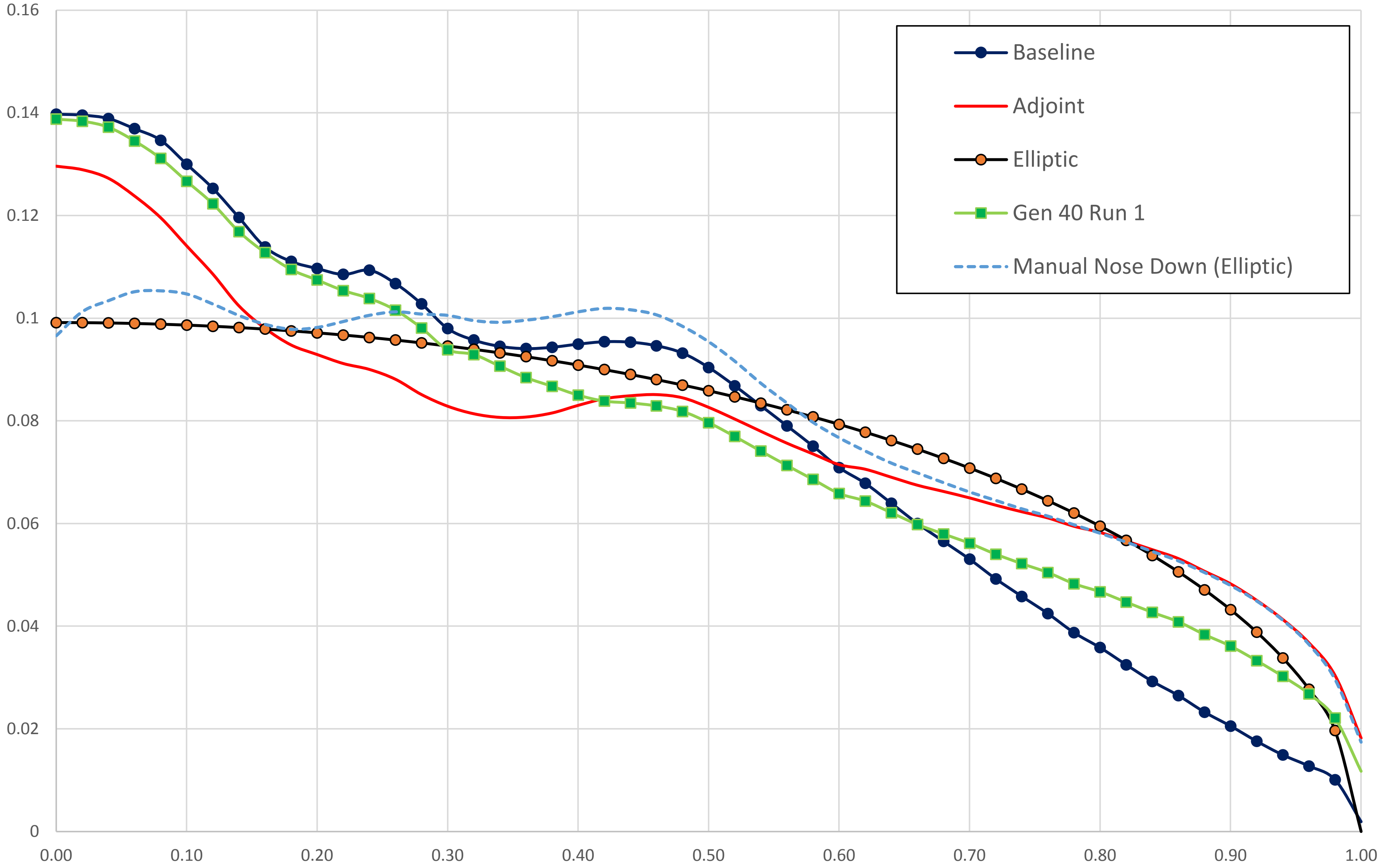
Acknowledgement

This work was supported by NASA's Advanced Air Transport Technology (AATT) Project.

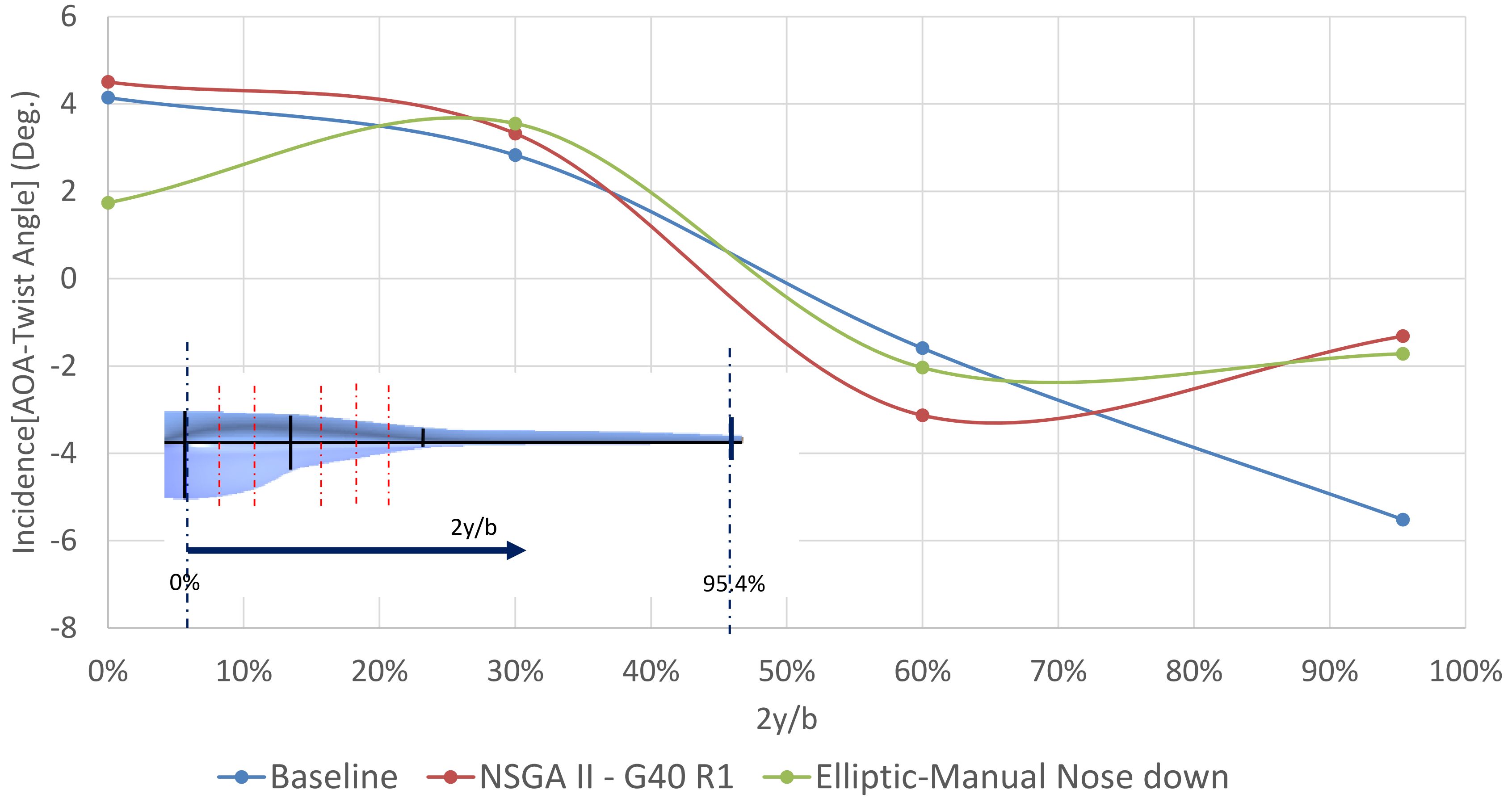
NSGA-II – 8 twist angles (PAI)



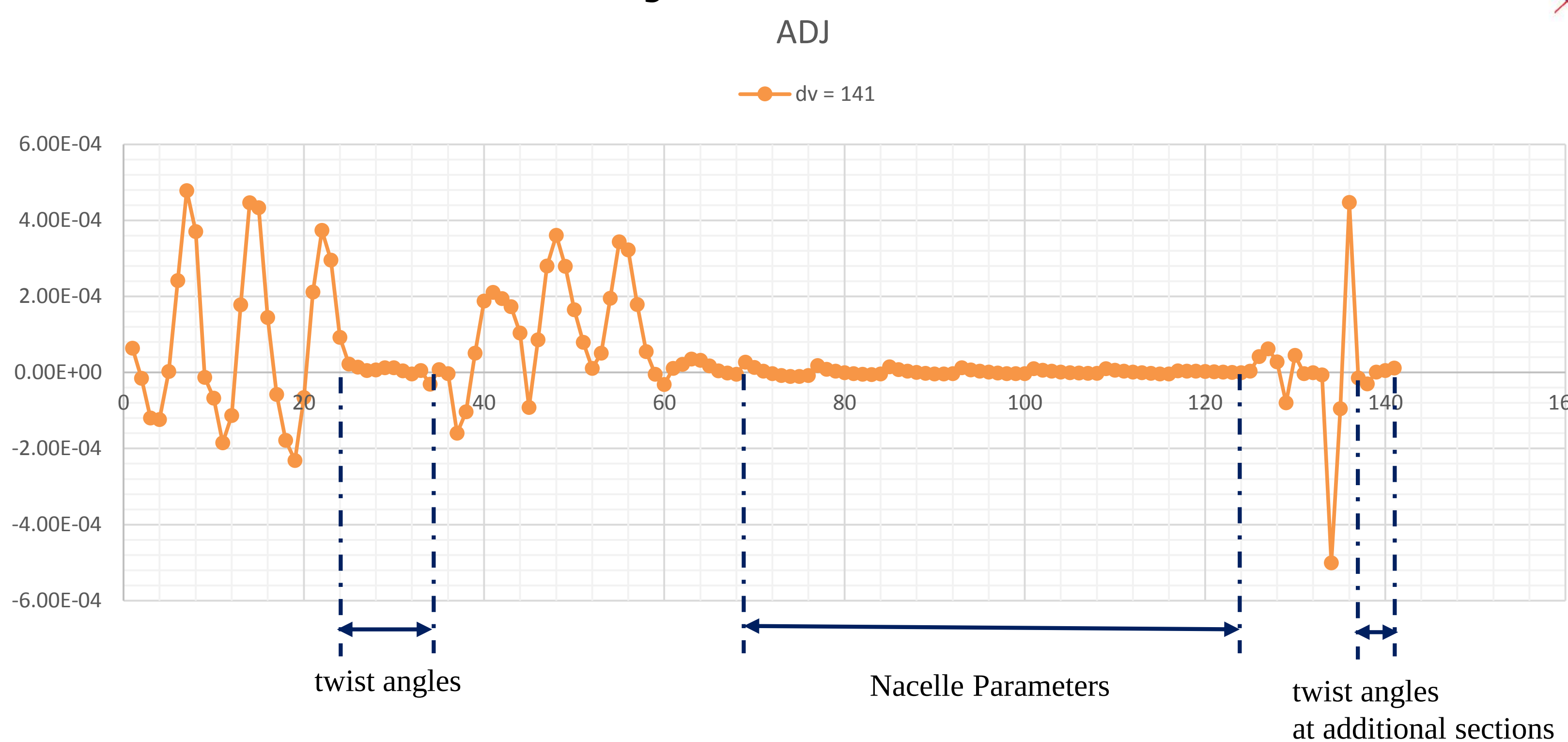
NSGA-II – 8 twist angles



Local Incidence Angle Comparison



Scaled Sensitivity of Nacelle Parameters



- The sensitivities of nacelle parameters scaled by 5 times and twist angle by 1.25 for both optimized cases.
- The shock strength on the nacelle scaled sensitivity case got weaker than the prime optimized design but the geometry resulted marginally larger drag due to increase of induced drag.

	C_{Di}	C_{Dw}	$C_{Di}+C_{Dw}$
Baseline	93.47%	6.53%	100.00%
Optimized	-17.72%	-4.89%	-22.61%
Nacelle SCLD	-14.36%	-6.14%	-20.50%