Phase I LEARN Final Meeting

Design, Analysis, and Evaluation of a Novel Propulsive Wing Concept

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Phase I LEARN Objectives

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• Develop a Propulsive Wing Concept by Designing a Transonic Laminar Flow Griffith/Goldschmied Airfoil
  – Design For Extended Laminar Flow
  – Explore the Possibilities of Pressure Thrust in a Transonic Section
  – Exploit Cross Flow Fans for the Suction System and Wake Filling

• Proposed Research Seeks to Address Need for Ultra-Efficient Commercial Vehicles and Transition to Low-Carbon, Low-Noise Propulsion

• New Wing Concept Will Directly Contribute to NASA’s SFW N+3 Configuration Goals for Aircraft Efficiency
Starting Point

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• Goldschmied Spanloader
  – t/c=31.5%
  – M*=0.45

• Baseline for New Design
  – Boeing N+4 Sugar Refined
    • M=0.70, C_l=0.86
    • New Design will Match Mission Performance
    • Quantify Net Benefit

Spoiler Alert:
-12% Reduced Block Fuel Burn per Seat
Phase I LEARN Objectives

• Project Broken Into Three Major Thrusts
  – Systems and Energy Balance (Illinois)
    • Evaluate the Feasibility of the Conceptual Wing Design
    • Assess: Do Benefits Outweigh System Costs?
    • Boeing N+4 SUGAR Refined Chosen as Baseline Platform
      – Suggested By NASA, Advanced Configuration, Designed For Similar Cruise Mach
  – Design New Griffith/Goldschmied Section, $M_\infty=0.7$ (RHRC)
    • Extended Natural Laminar Flow
    • Suction Based Trailing-Edge Recovery For Static Pressure Thrust
    • Wake Filling With Suction Mass Flow Ejected at the Trailing-Edge
  – Experimental Test of CFF and New Airfoil Section (Illinois)
    • Transonic Test of BLI CFF – Quantify Fan Performance
    • Low Speed Test of New Airfoil to Verify Ability to Efficiently Produce Static Pressure Thrust
Transonic Airfoil Concept

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Transonic Griffith/Goldschmied Concept Airfoil

- Boundary-Layer Suction
- Wake Filling Fan Exhaust
- Crossflow Fan

Benefits:
- Extended Laminar Flow
- Pressure Thrust
- Wake Filling

TeDP BLI Fan Installation

New Transonic Griffith/Goldschmied Wing Sections
Original Goldschmied Design

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- Pressure Thrust/Drag Parametric Results
  - Pressure Drag at $\alpha=0^\circ$ is $\int_0^c (C_{P,Upper} - C_{P,Lower})dy$
    - $+C_p dy = $ Pressure Drag
    - $-C_p dy = $ Pressure Thrust
  - To Minimize Pressure Drag
    - Small LE Radius to Reduce Stagnation Point Region $+C_p dy$
    - Thick Section To Increase $dy$ During Pressure Rise
    - Generate Lift With High $C_p$ Near Recovery Onset
    - Steep Suction Based Recovery to Positive Pressure
    - Favorable Gradients to Keep Displacement Thickness Low

Goldschmied Spanloader Section
Effect of Suction Velocity

- Goldschmied Section $t/c=31.5\%, M=0.245$
- Laminar Flow Plus Pressure Thrust
- Little Response to Suction Until $V_s/V_\infty > 0.020$
- Separation Virtually Gone at $V_s/V_\infty > 0.025$
- Very Non-Linear Response to Suction
- Low Critical Mach number
Transonic Airfoil Constraints

- Transonic Griffith/Goldschmied Section (M≈0.70, C_l=.86)
  - Different Design Constraints
    - Want Thin Section For Low Wave Drag (Keep Min. C_p around C_p*)
    - Want Large Leading-Edge Radius For Supercritical Flat-Top Pressure Distribution
    - Must Spread Lift Over Entire Chord
      - Trade-Off Between Favorable dp/dx for Transition and Ability to Generate Higher C_l
      - Flat Roof-Top Reduces dy
    - Steep Suction Based Recovery to Positive Pressure
      - Increasing Recovery Gradient and Required Suction Increases Local Mach/Shock Upstream of Suction Location
    - Favorable Gradients to Keep Displacement Thickness Low
    - Single Side Suction
      - Trade-Off Between Upper and Lower Surface Pressure Thrust/Drag
Airfoil Design Approach

• OVERFLOW Used for Analysis
  – NASA code, Reynolds Averaged Navier-Stokes, Structured Grid, Langtry-Mentor Transition Model

• Initial Efforts Used OpenMDAO to Iterate on OVERFLOW Solutions
  – Many Optimizers Tried (COBYLA, CONMIN, Genetic, NEWSUMT, SLSQP), but with Generally Poor Results
  – Non Linear Behavior with Suction Contributed to Difficulty

• Successful Approach was to Couple Inverse Airfoil Design Code Profoil to Specify Pressure Distributions with Analysis in OVERFLOW to Include Suction Slot

• Profoil is an Inviscid Euler Code Capable of Multiple Constraints
Grid Resolution

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- Code Wasn’t Capturing the Shedding from Trailing Edge
- Increased Grid Points 600->900
- Increased Points on TE 9->21
- Significant Effect on Transition Location
Airfoil Design Result

Comparison of 2D Sugar Refined and OVERFLOW Predicted Results

\( \frac{v}{c} = 12.48\%, M_a = 0.70, Re = 16.2 \times 10^6, h = 40\text{kft}, c = 144.7, \frac{x}{c_{\text{crit}}} = 0.825 - 0.875, C_{\mu} = \left(\frac{\rho u^2 L}{(\rho V_c)^2}\right) = 0.00013 - 0.00014 \)

**Design Point**, \( \alpha \approx 0^\circ, C_l \approx 0.86 \)
- **Sugar Refined**: \( C_d = 0.01371 \)
- **RHRC125.B1.M70**: \( C_d = 0.00515 \)
- **RHRC125.T1.M70**: \( C_d = -0.00041 \)

**62% \( C_d \) Reduction**

**100% \( C_d \) Reduction**

**Transition Location**
- \( \frac{x}{c_{\text{up}}} = 0.57 \)
- \( \frac{x}{c_{\text{low}}} = 0.45 \)

**Drag**
- **Upper+Lower Press Drag**
- **Trailing-Edge Press Drag**
- **Upper+Lower Press Drag**
- **Trailing-Edge Press Drag+Mass Flow**

**Pressure Distribution**
- \( \alpha = 0^\circ \)
- **Suction Location**
Wind Tunnel Model Design

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Wind Tunnel Model Design

• Because of small scale, CFF flow is simulated
Low-Speed Wind Tunnel Test

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- Power failure at fabrication shop delayed the model delivery
- Test is currently underway
- A high-speed (M=0.70) wind tunnel test is required to validate the airfoil design, but was outside of the scope of the Phase I program
Cross-Flow Fan Overview

• Investigation of embedded cross-flow fan in transonic flow
  – Also known as transverse fan, typically used in HVAC systems
  – Compact geometry, easily embedded in wing
  – Span-integrated effect, spanwise length of fan can be increased to match span of wing

• Characterize the power requirements and fan performance in transonic flow
  – Suction and pressure recovery
  – Power required for operation
CFF Aerodynamics

Key aerodynamic characteristics

- Flow enters the fan radially and exits tangentially
- Interior flow is governed by two vortex regions
- Fan housing is largest factor in determining performance
  - Rear wall
  - Vortex wall
  - Gap size
  - Ratio of blades inner to outer radii
- CFD predicts that there is little sensitivity to boundary layer ingestion
CFF Experimental Facility

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- Supersonic wind tunnel adapted for transonic flow
  - Blowdown-type configuration
  - New nozzle designed for subsonic flow
  - Test section machined to incorporate fan housing into tunnel wall
  - CFF spans tunnel, mounted with bearings in both of the tunnel walls
CFF Experiment Configuration

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- Test section details
  - 3.4” diameter fan, 5” span
  - 7.5° diffusing inlet ramp for radial flow
  - Vortex wall/expansion surface manufactured with SLA printing
  - Probe survey location shown

- Fan driven by 3 hp motor
  - Pulley system designed for 3,000 to 15,000 RPM
  - Variable frequency AC Drive for control
  - 208 V power supply
CFF Measurements

- Data collection
  - Probe surveys in exit duct
    - Hotwire ($V$)
    - Thermocouple ($T_o$)
    - Total Pressure ($P_o$)
    - 0.05” resolution
  - Power Measurements
    - Torque transducer inline with fan
    - RPM and Torque recorded
CFF Measurement Results

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- **Power Measurements**
  - Fan power as $f(M, \text{RPM})$
  - Data up to $M = 0.73$

- **Duct Surveys**
  - $M = 0.4, 0.5, 0.6$
  - $\text{RPM} = 5500, 7000$

<table>
<thead>
<tr>
<th>Mach</th>
<th>RPM</th>
<th>$P_o \text{ (lbs/ft}^2\text{)}$</th>
<th>$T_o \text{ (R)}$</th>
<th>$V \text{ (ft/s)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.41</td>
<td>5114.23</td>
<td>2066.33</td>
<td>516.81</td>
<td>168.27</td>
</tr>
<tr>
<td>0.41</td>
<td>5993.73</td>
<td>2072.46</td>
<td>526.65</td>
<td>178.75</td>
</tr>
<tr>
<td>0.52</td>
<td>5566.38</td>
<td>2035.77</td>
<td>521.13</td>
<td>182.26</td>
</tr>
<tr>
<td>0.52</td>
<td>6925.31</td>
<td>2059.63</td>
<td>537.05</td>
<td>194.68</td>
</tr>
<tr>
<td>0.59</td>
<td>5698.14</td>
<td>2021.91</td>
<td>525.51</td>
<td>196.41</td>
</tr>
</tbody>
</table>
Suction-Based Recovery

• Surface Pressure Measurements
  – Fan-off case indicates flow separation across expansion surface
  – 5500 and 7000 RPM cases exhibit effective pressure recovery
    • Small increases in pressure from suction with further increases in RPM
  – Results indicate that suction produced by the CFF is more than sufficient to keep flow attached in transonic conditions

• Flow properties and power requirements for suction-based pressure recovery and attachment scaled to aircraft conditions
CFF Power/Flow Scaling

Scaling results to full sized aircraft in cruise using:

- Power coefficient: \( \lambda = \frac{W_s}{\frac{1}{2}\rho D_o U_o^3 b} \)

- Flow coefficient: \( \phi = \frac{V_\infty}{\omega D_o} \)

- Both calculated from experimental data

- Aircraft fan RPM computed by matching flow coefficients

- Aircraft CFF power consumption computed by integrating \( \frac{W_s}{b} \) across the span

\[
P = 2 \int_0^{B/2} \frac{W_s}{b} \, dy \\text{where } \frac{W_s}{b} = \frac{1}{2} \rho D_o U_o^3 \lambda
\]
CFF Power Requirement

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<table>
<thead>
<tr>
<th>Pre-scaled test values</th>
<th>Scaled aircraft values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_s$ [kW]</td>
<td>$P$ [kW]</td>
</tr>
<tr>
<td>2.8808</td>
<td>187.58</td>
</tr>
<tr>
<td>$b$ [ft]</td>
<td>$B$ [ft]</td>
</tr>
<tr>
<td>0.4167</td>
<td>84.8</td>
</tr>
<tr>
<td>$\rho$ [slug/ft$^3$]</td>
<td>$\rho$ [slug/ft$^3$]</td>
</tr>
<tr>
<td>0.0021364</td>
<td>0.0005428</td>
</tr>
<tr>
<td>$D_o$ [in]</td>
<td>$D_{o,root}$ [in]</td>
</tr>
<tr>
<td>3.457</td>
<td>11.28</td>
</tr>
<tr>
<td>$U_o$ [ft/s]</td>
<td>$D_{o,tip}$ [in]</td>
</tr>
<tr>
<td>85.395</td>
<td>4.94</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$U_o$ [ft/s]</td>
</tr>
<tr>
<td>26.61</td>
<td>76.8</td>
</tr>
<tr>
<td>$M$</td>
<td>$M$</td>
</tr>
<tr>
<td>0.7014</td>
<td>0.7</td>
</tr>
<tr>
<td>RPM</td>
<td>RPM</td>
</tr>
<tr>
<td>5661.3</td>
<td>Varies with $D_o$</td>
</tr>
</tbody>
</table>

- Calculation requires the assumption that the power coefficient $\lambda$ and the fan tip speed be held constant across the span
- Tip speed required for the aircraft is lower than the speed obtained in experiment
- Power consumption of the CFF system on Boeing SUGAR N+4 aircraft predicted to be **187.58 kW**
  - Power requirement used in the systems analysis
Systems Analysis

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GOALS

- Understand the effects of the transonic Griffith/Goldschmeid airfoil via a systems-level analysis
- Interdisciplinary aircraft synthesis program for conceptual design
  - Design range: 3500 nm
  - TOGW: 138,000 lb
  - Cruise Mach: 0.70
  - Cruise $C_L$: 0.60
  - Block Fuel/Seat (900 nm): 42.4 lb

Trade Study: Aero, Propulsion, Weights

- AERODYNAMIC MATCHING
- TRAJECTORY MATCHING
- AVID ACS 5.04 (ACSYNT)
- N+4 SUGAR Refined
- GEOMETRY MATCHING
- PROPULSION MATCHING
- WEIGHT MATCHING
3 Independent variables

• Aerodynamics:
  – Highest effect on fuel burn
  – Based on CFD/wind tunnel testing of designed airfoil

• Propulsion:
  – Minimally affects fuel burn
  – Power extracted from A/C integrated drive generator (IDG)
  – Based on wind tunnel results for cross-flow fan

• Weights:
  – Based on implementation of crossflow fan system into wing.
Aero Modeling (1)

• Need to tie in CFD and wind tunnel experimental airfoil results into ACS.
• ACS aerodynamic model based on full A/C
• Process:
  – Match SUGAR Refined ACS results using a first/second order approach
  – Determine spanwise distribution of crossflow fan
  – Model wing airfoil distribution using nonlinear lifting line theory
  – Determine final wing aerodynamics and combine to obtain A/C aero
  – Input new aerodynamic data into ACS
Aero Modeling (2)

- First/second order approach based on Anderson, Nicolai and Carichner, and Phillips used.
- A/C aerodynamics split into wing and horizontal tail

\[
C_{\text{L}_{a/c}} = C_{\text{LW}} + \frac{S_{\text{HT}}}{S_{\text{W}}} C_{\text{LHT}}
\]

\[
C_{\text{LW}} = (\alpha_{\text{geo}} - \alpha_{\text{0W}} + i_{\text{W}}) C_{\text{LW}_\alpha}
\]

\[
C_{\text{LHT}} = (\alpha_{\text{geo}} - \alpha_{\text{0HT}} + i_{\text{H}} - \varepsilon_{\text{d}}) C_{\text{LHT}_\alpha}
\]

\[
C_{\text{D}_{\text{ac}}} = C_{\text{D}_W} + C_{\text{D}_{\text{HT}}} + C_{\text{D}_{\text{rest}}}
\]

\[
C_{\text{D}_W} = C_{\text{D}_{\text{Wmin}}} + k_{\text{W}} C_{\text{LW}}^2 + \frac{C_{\text{LW}}^2}{\pi e_{\text{W}} A R_{\text{W}}}
\]

\[
C_{\text{D}_{\text{HT}}} = C_{\text{D}_{\text{HT0}}} + k_{\text{HT}} C_{\text{LHT}}^2 + \frac{C_{\text{LHT}}^2}{\pi e_{\text{HT}} A R_{\text{HT}}}
\]

\[
C_{\text{D}_{\text{rest}}} = C_{\text{D}_{\text{f, body}}} + C_{\text{D}_{\text{f, VT}}} + C_{\text{D}_{\text{interference}}}
+ C_{\text{D}_{\text{wave}}} + C_{\text{D}_{\text{ext}}}
\]
Aero Modeling (3)

- Values for $\alpha_{0lW}, i_W, i_{HT}, k_W, k_{HT}$ iteratively converged upon to match SUGAR Refined ACS output

\[
C_{l_W} = (\alpha_{geo} - \alpha_{0l} + i_W) (m_0)_{M\neq 0}
\]

\[
C_{d_W} = C_{D_0} + k_W C_{l_W}^2
\]
Aero Modeling (4)

Wing CAD Model (OpenVSP/SolidWorks) – Boeing 737 NG wing design

- Slat
- Kruger Flap
- Outboard Flap (double-slotted)
- Inboard Flap (double-slotted)
Aero Modeling (4)

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Wing CAD Model (OpenVSP/SolidWorks) – Boeing 737 NG wing design

Crossflow Fan till Aileron (70-72% of span)
- Replaces flaps
- Located at 85% chord since suction is at 82.5-87.5% chord
- 5.2% (local) chord diameter
- 5 – 11.3 inch max diameter
Wing geometry transferred to MATLAB

Nonlinear lifting line theory used to compute wing performance with varying spanwise airfoil distribution

70% of wing modeled uses RHRC125.B1.M70 airfoil (green)

30% uses first/second order approach baseline wing airfoil (purple)
• Aerodynamic input data table for ACS
  – Based on Mach number, altitude, and angle of attack
  – Additional RHRC125.B1.M70 data at M=0.2 used for table
  – Interpolation based on Mach number. Aero coeffs. constant with altitude.
Propulsion Modeling

- Based on Boeing SUGAR Report
  - Aircraft uses advanced generation of ‘787 No-Bleed Electrical System Architecture’
  - SUGAR Refined Requirements (Peak)
    - Hydraulics: 60 Hp $\rightarrow$ 45 kW $\rightarrow$ 56.3 kVA
    - Electric: 540 kVA
    - Crossflow Fan: 187.58 kW $\rightarrow$ 234.5 kVA
    - Total Installed Aircraft Power: 830.8 kVA

Figure 11. Instantaneous power consumption over a mission profile for a sample Boeing 737 model

Weights Estimation (1)

- From Rudolph (Progress in Aerospace Sciences), 1996

### Table 4.1. Trailing-edge flap specific weights (weights in lb/ft² of stowed flap area)

<table>
<thead>
<tr>
<th>Flap type</th>
<th>Single-slotted</th>
<th>Fixed vane/main</th>
<th>Articulating vane/main</th>
<th>Double-slotted</th>
<th>Triple-slotted</th>
<th>Single-slotted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support</td>
<td>Hooked track</td>
<td>Hooked track</td>
<td>Hooked track</td>
<td>Hooked track</td>
<td>Hooked track</td>
<td>Link/Track end support</td>
</tr>
<tr>
<td>Flap panels</td>
<td>2.7</td>
<td>3.0</td>
<td>3.5</td>
<td>4.8</td>
<td>5.5</td>
<td>2.7</td>
</tr>
<tr>
<td>Supports</td>
<td>3.0</td>
<td>3.2</td>
<td>3.8</td>
<td>4.7</td>
<td>5.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Actuation</td>
<td>2.2</td>
<td>2.2</td>
<td>2.3</td>
<td>2.4</td>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Fairing/flap area</td>
<td>(0.45)</td>
<td>(0.45)</td>
<td>(0.50)</td>
<td>(0.55)</td>
<td>(0.60)</td>
<td>(0.05)</td>
</tr>
<tr>
<td>Fairing</td>
<td>1.0</td>
<td>1.0</td>
<td>1.15</td>
<td>1.30</td>
<td>1.40</td>
<td>0.10</td>
</tr>
<tr>
<td>Total flap</td>
<td>8.90</td>
<td>9.40</td>
<td>10.75</td>
<td>13.20</td>
<td>15.00</td>
<td>6.30</td>
</tr>
</tbody>
</table>

### Table 4.2. Specific weights for leading-edge devices (weights given in lb/ft²)

<table>
<thead>
<tr>
<th>Type</th>
<th>Rigid Krueger</th>
<th>VC Krueger</th>
<th>Three-position slat with slave tracks</th>
<th>Three-position slat without slave tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed leading edge</td>
<td>2.25</td>
<td>2.25</td>
<td>2.2</td>
<td>2.1</td>
</tr>
<tr>
<td>Moving panels</td>
<td>1.5</td>
<td>2.1</td>
<td>2.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Actuation</td>
<td>1.5</td>
<td>1.75</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Total flap</td>
<td>5.25</td>
<td>6.1</td>
<td>6.0</td>
<td>5.8</td>
</tr>
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</table>
Weights Estimation (2)

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Baseline

<table>
<thead>
<tr>
<th>GROUP</th>
<th>WEIGHT (LB)</th>
<th>% TOGW</th>
</tr>
</thead>
<tbody>
<tr>
<td>WING</td>
<td>13,780</td>
<td>10.1%</td>
</tr>
<tr>
<td>BENDING MATERIAL</td>
<td>5,754</td>
<td>4.2%</td>
</tr>
<tr>
<td>SPAR WEBS</td>
<td>994</td>
<td>0.7%</td>
</tr>
<tr>
<td>RIBS AND BULKHEADS</td>
<td>1,091</td>
<td>0.8%</td>
</tr>
<tr>
<td>AERODYNAMIC SURFACES</td>
<td>3,151</td>
<td>2.3%</td>
</tr>
<tr>
<td>SECONDARY STRUCTURE</td>
<td>2,791</td>
<td>2.0%</td>
</tr>
<tr>
<td>TAIL</td>
<td>2,676</td>
<td>2.0%</td>
</tr>
<tr>
<td>FUSELAGE</td>
<td>14,946</td>
<td>11.0%</td>
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<tr>
<td>LANDING GEAR</td>
<td>5,052</td>
<td>3.7%</td>
</tr>
<tr>
<td>NACELLE &amp; PYLON</td>
<td>5,392</td>
<td>4.0%</td>
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<tr>
<td>PROPULSION</td>
<td>9,898</td>
<td>7.3%</td>
</tr>
<tr>
<td>ENGINES</td>
<td>9,280</td>
<td>6.8%</td>
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<tr>
<td>FUEL SYSTEM</td>
<td>618</td>
<td>0.5%</td>
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<tr>
<td>FLIGHT CONTROLS</td>
<td>3,106</td>
<td>2.3%</td>
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<tr>
<td>COCKPIT CONTROLS</td>
<td>252</td>
<td>0.2%</td>
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<tr>
<td>SYSTEM CONTROLS</td>
<td>2,853</td>
<td>2.1%</td>
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<tr>
<td>POWER SYSTEMS</td>
<td>4,211</td>
<td>3.1%</td>
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<tr>
<td>AUXILIARY POWER UNIT</td>
<td>1,014</td>
<td>0.7%</td>
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<tr>
<td>HYDRAULICS</td>
<td>901</td>
<td>0.7%</td>
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<tr>
<td>ELECTRICAL</td>
<td>2,297</td>
<td>1.7%</td>
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<td>INSTRUMENTS</td>
<td>773</td>
<td>0.6%</td>
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<tr>
<td>AVIONICS &amp; AUTOPILOT</td>
<td>1,504</td>
<td>1.1%</td>
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<tr>
<td>FURNISHINGS &amp; EQUIPMENT</td>
<td>9,115</td>
<td>6.7%</td>
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<td>AIR CONDITIONING</td>
<td>1,441</td>
<td>1.1%</td>
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<tr>
<td>ANTI-ICING</td>
<td>112</td>
<td>0.1%</td>
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<tr>
<td>MANUFACTURER’S EMPTY WEIGHT (MEW)</td>
<td>72,006</td>
<td>52.8%</td>
</tr>
<tr>
<td>OPERATIONAL ITEMS</td>
<td>7,207</td>
<td>5.3%</td>
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<tr>
<td>OPERATIONAL EMPTY WEIGHT (OEW)</td>
<td>79,213</td>
<td>58.1%</td>
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<tr>
<td>USABLE FUEL</td>
<td>26,399</td>
<td>19.4%</td>
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<td>DESIGN PAYLOAD</td>
<td>30,800</td>
<td>22.6%</td>
</tr>
<tr>
<td>TAKEOFF GROSS WEIGHT (TOGW)</td>
<td>136,412</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

Final A/C

- Remove inboard/outboard flap actuation and fairing \( \rightarrow - 683.1 \text{ lb} (\Delta W_{\text{wing}} = -5\%) \)
- 787 Architecture (4 IDG @ 250kVA each)
  - According to Kennett (1971) \( \rightarrow 1.3 \text{ kVA/lb} \)
  - Crossflow Requirement \( \rightarrow + 180.4 \text{ lb} \)
- Crossflow Fan Motors (Green et. al., 2012)
  - \( W_{\text{motor}} = 2.62 * P_{\text{max}}^{0.739} = + 148 \text{ lb} \)
- Structural weight of fan, support structure, and ducting not included
- Minimum bound
Final Systems Analysis

3 Independent variables

- **Aerodynamics:**
  - Designed wing uses RHRC125.B1.M70 airfoil for 70% of span

- **Propulsion:**
  - Crossflow Fan Power requirement: 234.5kVA

- **Weight:**
  - Current empty weight change: -354.7 lb (lower bound)

\[ W_G = 131,722 \text{ lb} \]

Block Fuel / Seat (900nm) = 37.28%

% 11.8 reduction in fuel consumption

10% increase in wing weight \(\Rightarrow\) 11.4% reduction
Conclusions

- Transonic, ultra-low drag airfoil section developed for commercial transport vehicles
  - Utilizes suction-based pressure recovery
  - Balances tradeoffs associated with boundary-layer transition, suction power, static pressure thrust, thickness (wave drag), and power required
- Airfoil section utilizes suction through embedded cross-flow fan
  - Span-integrated effect
  - Provides required suction and pressure recovery at transonic speeds
  - Power requirements within capabilities of typical generator systems
- Systems analysis reveals cruise benefit
  - **11.8%** reduced fuel burn for Boeing N+4 Sugar Refined aircraft configuration
  - Performance matching of prescribed mission
  - System-level impact from changing drag, weight, and power requirements
  - Applied to advanced concept design: **59.8%** reduction in fuel burn when compared to current 737 configuration
Future Work

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• Integration of CFF into High-Lift System
  – Capabilities for STOL, blown flaps and control surfaces
  – Reduced weight and complexity
  – Full mission profile impact

• Transonic Wind Tunnel Test
  – High-speed test required to validate airfoil design
  – Large-scale model allows for embedded CFF

• Challenges
  – Transonic testing and transonic models are expensive
  – Phase II program only allows 1 year timeline for design, test, and analysis
BACKUP SLIDES
# Aerodynamic Modeling

**Leading Edge Aeronautics Research for NASA**

**Lift**

\[
C_{L_{ac}} = C_{LW} + C_{LHT}
\]

\[
C_{LW} = (\alpha_{geo} - \alpha_{0l} + i_W)C_{LW\alpha}
\]

\[
C_{LHT} = \left(\alpha_{geo} + i_h - (\varepsilon_0 + \frac{d\varepsilon}{d\alpha}\alpha_{geo})\right)C_{LHT\alpha}
\]

- **To calculate** $C_{L\alpha}$
  
  $C_{l\alpha} = 2\pi = (m_0)_{M=0}$

  \[
  (m_0)_{M\neq0} = \frac{(m_0)_{M=0}}{\sqrt{1 - M^2}}
  \]

  \[
  (m)_{\Delta=0} = \frac{m_0}{1 + [m_0(1 + \tau)/(\pi AR)]}
  \]

  $C_{L\alpha} = m = (m)_{\Delta=0}\cos(\Delta)$

  Compressibility corrections

  Finite wing corr.

  Sweep corr.

  $C_{lW} = (\alpha_{geo} - \alpha_{0l})(m_0)_{M\neq0}$

  $C_{lHT} = (\alpha_{geo})(m_0)_{M\neq0}$

**Drag**

\[
C_{D_{ac}} = C_{D_W} + C_{D_{HT}} + C_{D_{rest}}
\]

\[
C_{D_W} = C_{d\_W} + \frac{C_{LW}^2}{\pi e AR}
\]

\[
C_{d\_W} = C_{D0_W} + k_{visc1}C_{l\_W}^2
\]

\[
C_{D_{HT}} = C_{d\_HT} + \frac{C_{LHT}^2}{\pi e AR}
\]

\[
C_{d\_HT} = C_{D0HT} + k_{visc2}C_{l\_HT}^2
\]

\[
e = \frac{1}{1 + \delta}
\]
Wing Modeling

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Nonlinear Lifting Line

Spanwise Panels = 20
Spanwise Stations = 21

D (relaxation parameter) = 0.05
$\rightarrow$ From Anderson

Funk and McCormick Method used

- Circulation distribution calculated at each panel.
- Circulation distributions created shed vorticity ($\Gamma_{SV}$)
- Extension of Biot-Savart law used to calculated velocity induced at each panel by the shed vortices
- Works on swept, tapered, and dihedral wings.
NLLT Implementation w/ Mike39

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- 70% of wing modeled uses Mike39 TE Blowing airfoil
- 30% uses First/Second order wing airfoil