ROLLING HILLS RESEARCH
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ILLINOIS

Leading Edge Aeronautics Research for NASA

Phase I LEARN Final Meeting

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

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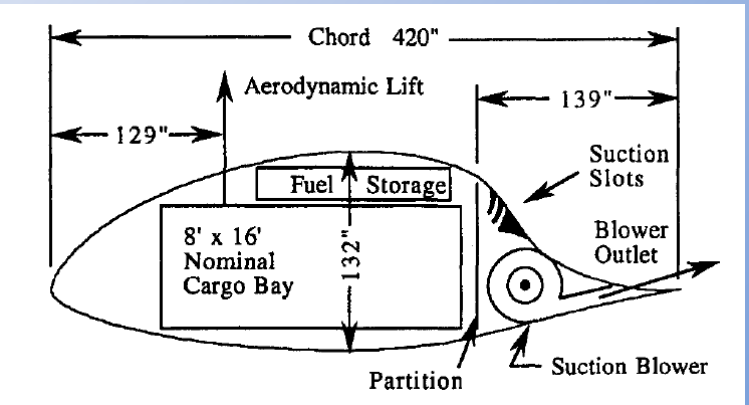
Phase I LEARN Objectives

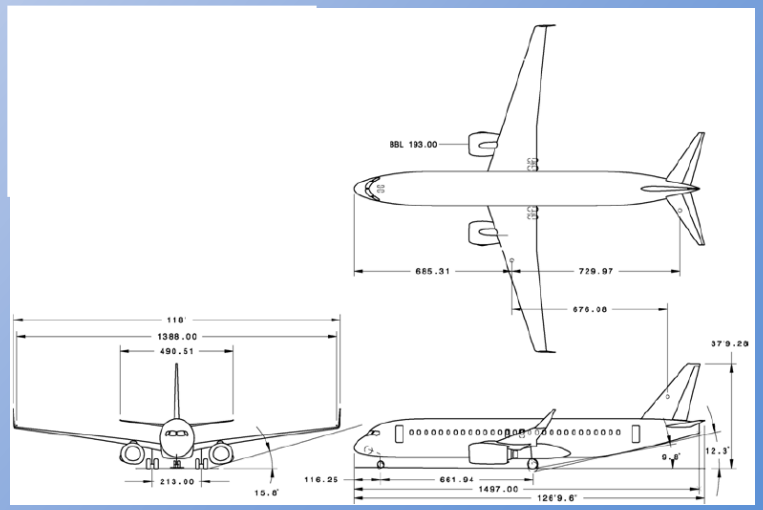
- Develop a Propulsive Wing Concept by Designing a Transonic Laminar Flow Griffith/Goldschmied Airfoil
  - Design For Extended Laminar Flow
  - Explore the Possibilities of Pressure Thrust in a Transonic Section
  - Exploit Cross Flow Fans for the Suction System and Wake Filling
- Proposed Research Seeks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

- 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

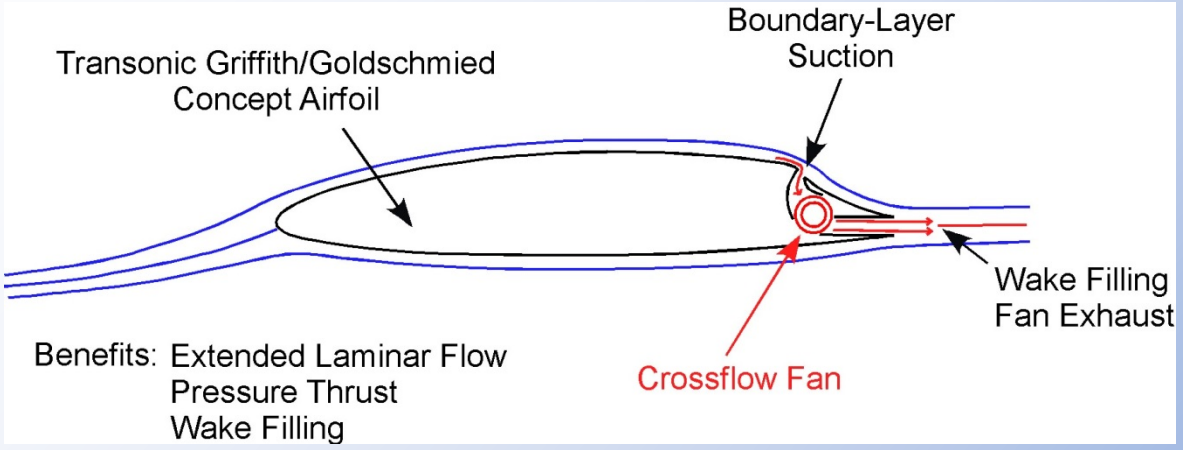


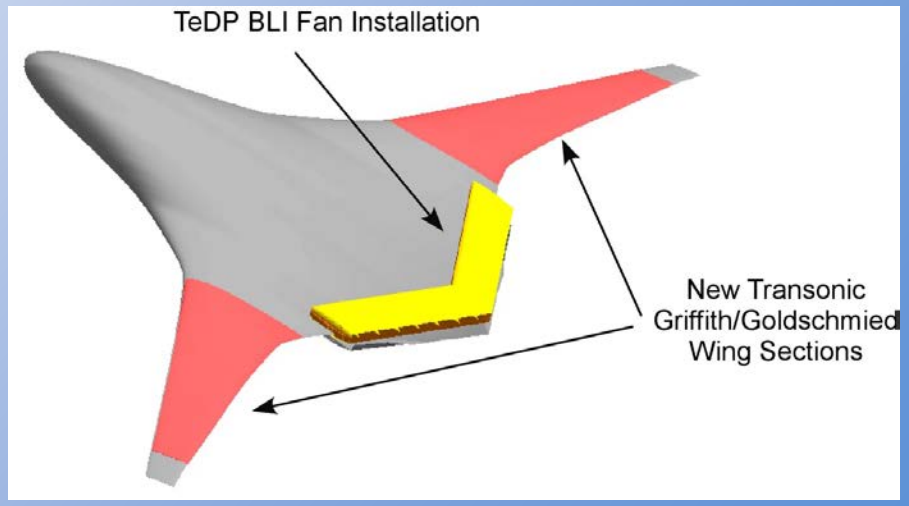
Spoiler Alert:
-12% Reduced Block Fuel Burn per Seat

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_∞=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

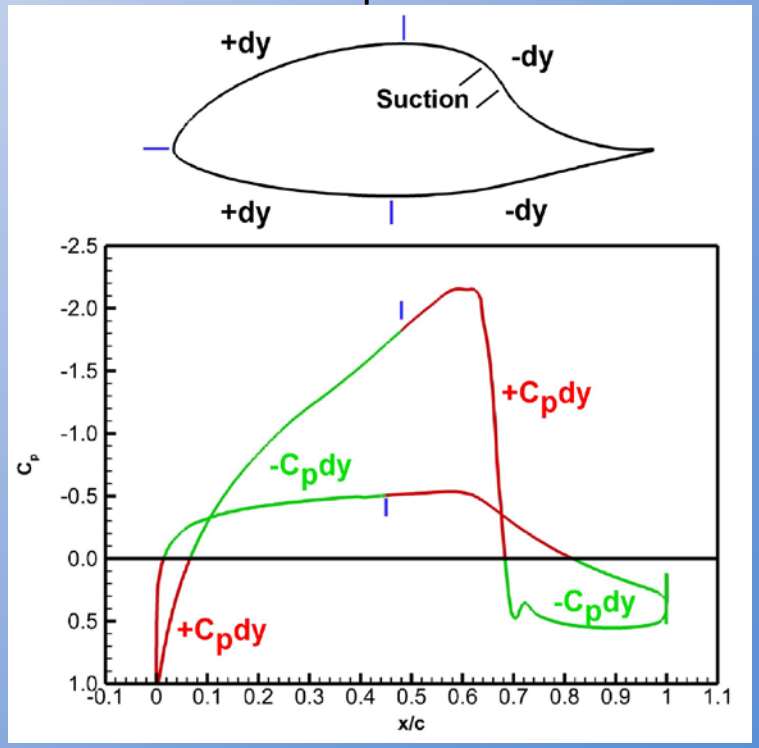




Original Goldschmied Design

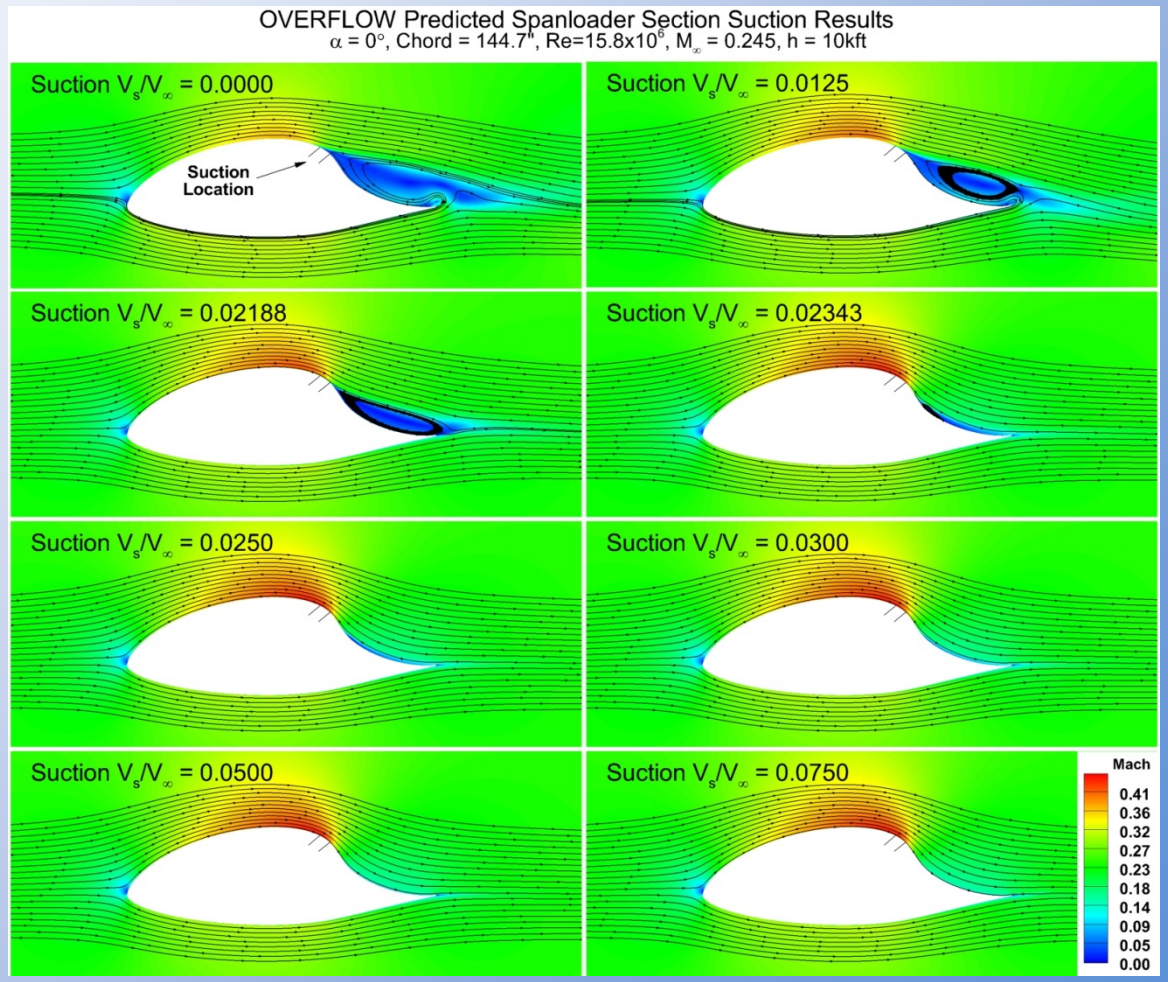
- Pressure Thrust/Drag Parametric Results
  - Pressure Drag at α=0° is $\int_0^c (C_{P,Upper} - C_{P,Lower})dy$
    - $+C_p dy$ = Pressure Drag
    - $- C_p dy$ = Pressure Thrust
  - To Minimize Pressure Drag
    - Small LE Radius to Reduce Stagnation Point Region $+C_p dy$
    - Thick Section To Increase 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



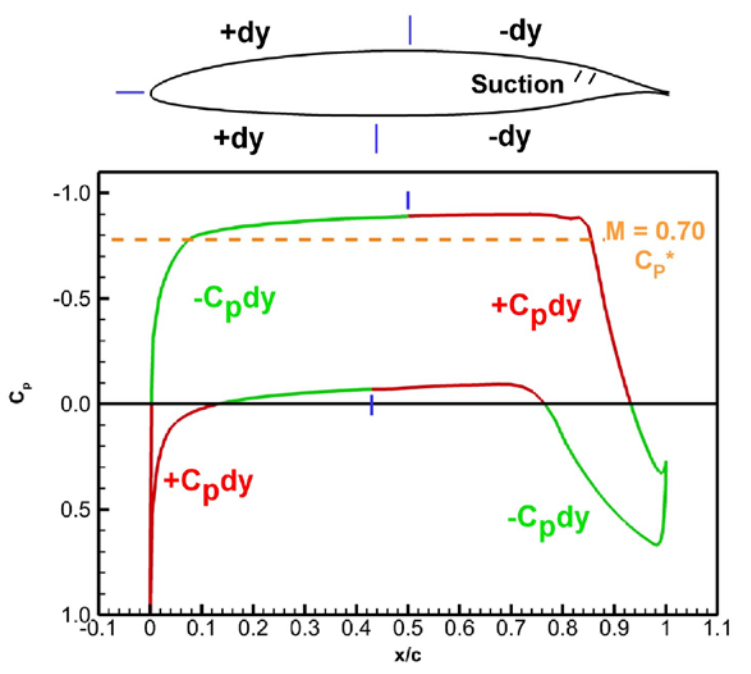
Effect of Suction Velocity

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



Transonic Airfoil Constraints

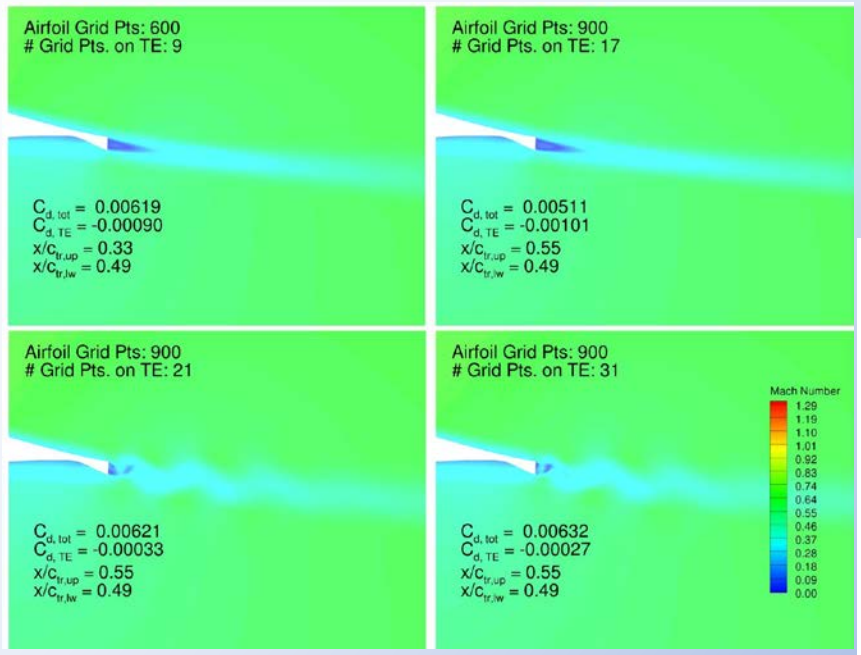
- Transonic Griffith/Goldschmied Section ($M \approx 0.70$, $C_l = .86$)
  - Different Design Constraints
    - Want Thin Section For Low Wave Drag (Keep Min. C_p around C_p^*)
    - Want Large Leading-Edge Radius For Supercritical Flat-Top Pressure Distribution
    - Must Spread Lift Over Entire Chord
      - 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



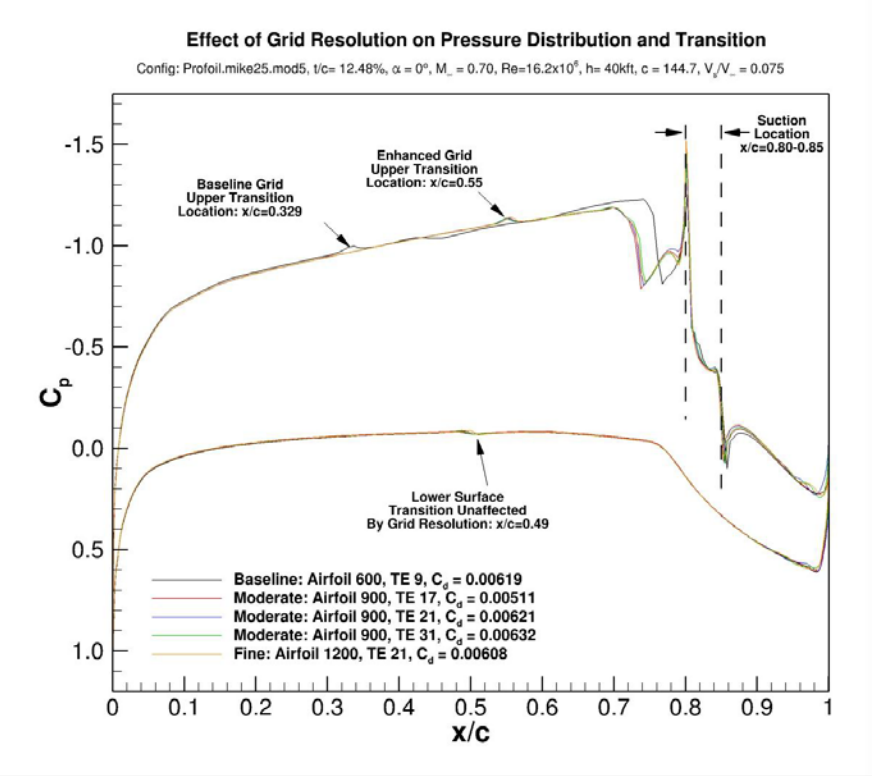
Airfoil Design Approach

- 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



- 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

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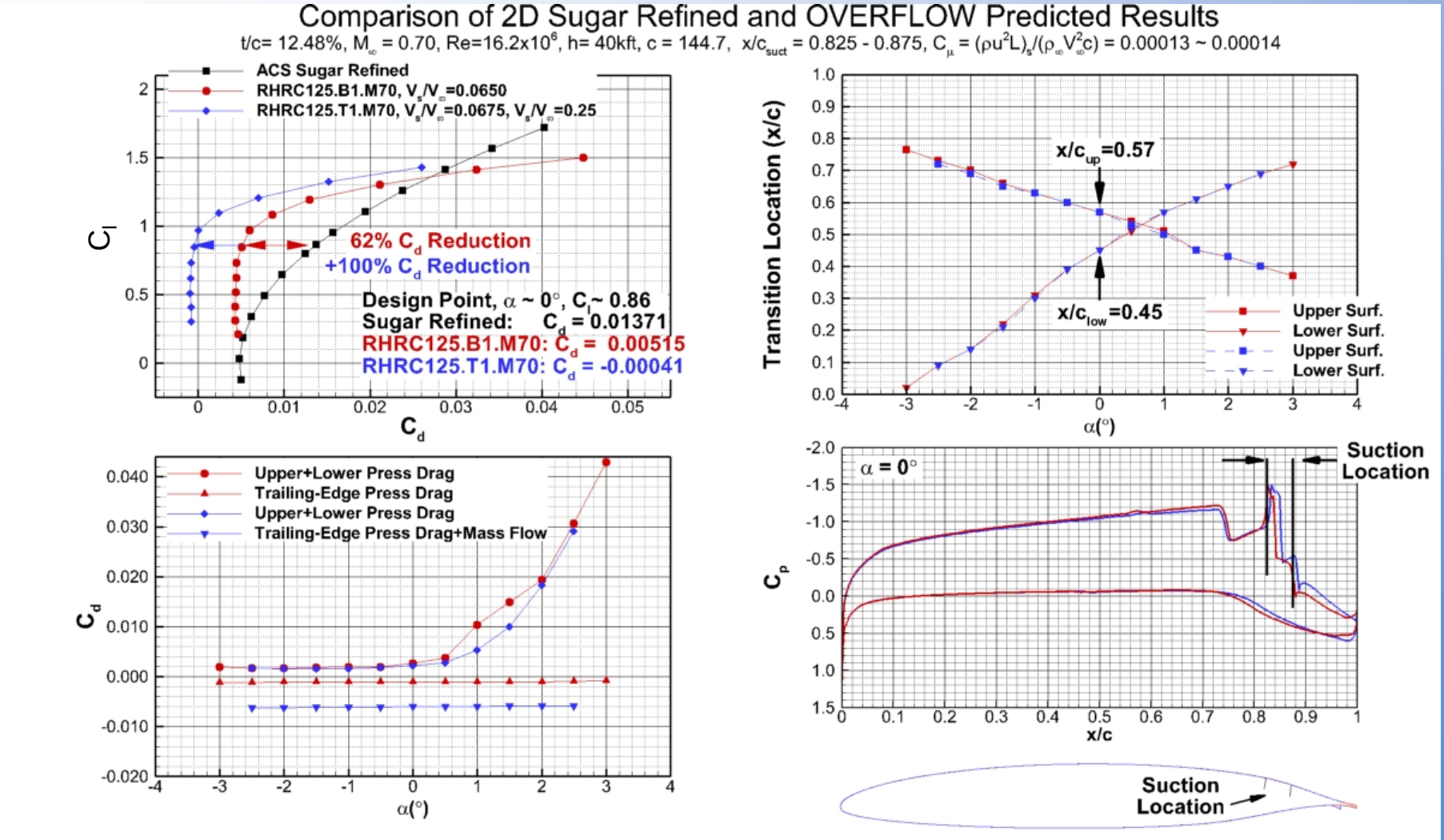
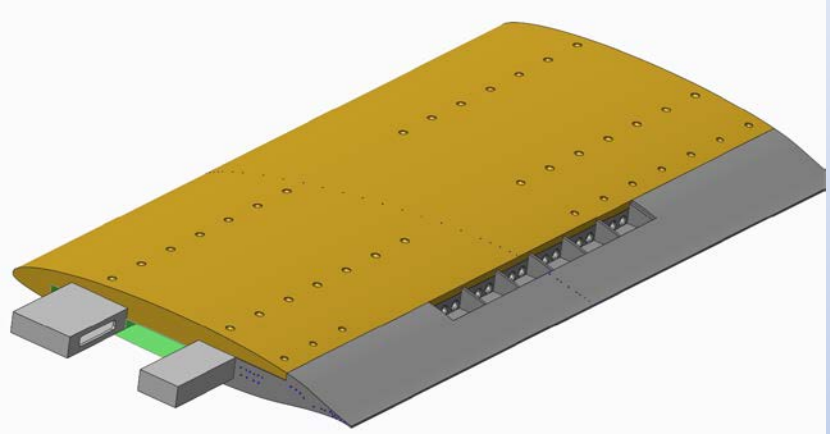
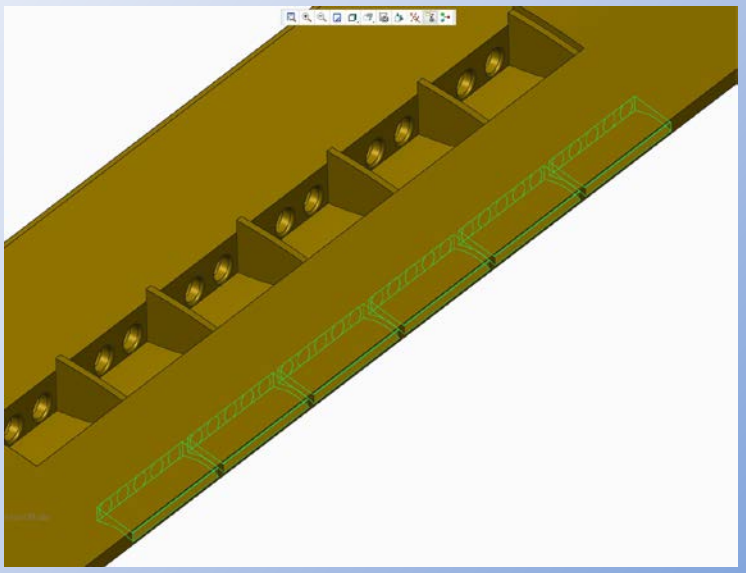
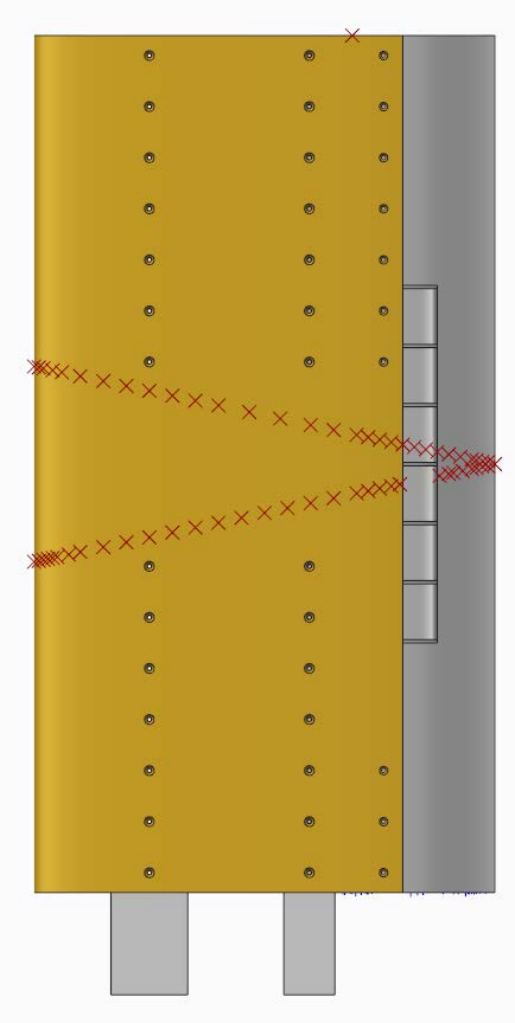


Wind Tunnel Model Design

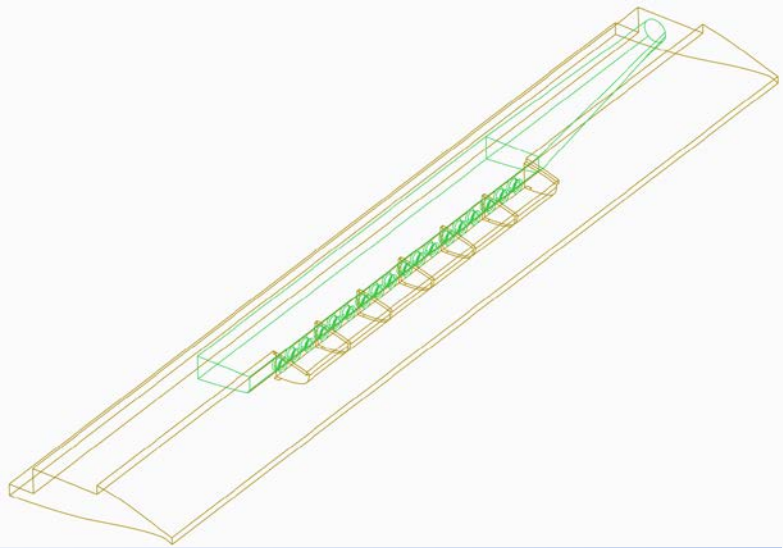


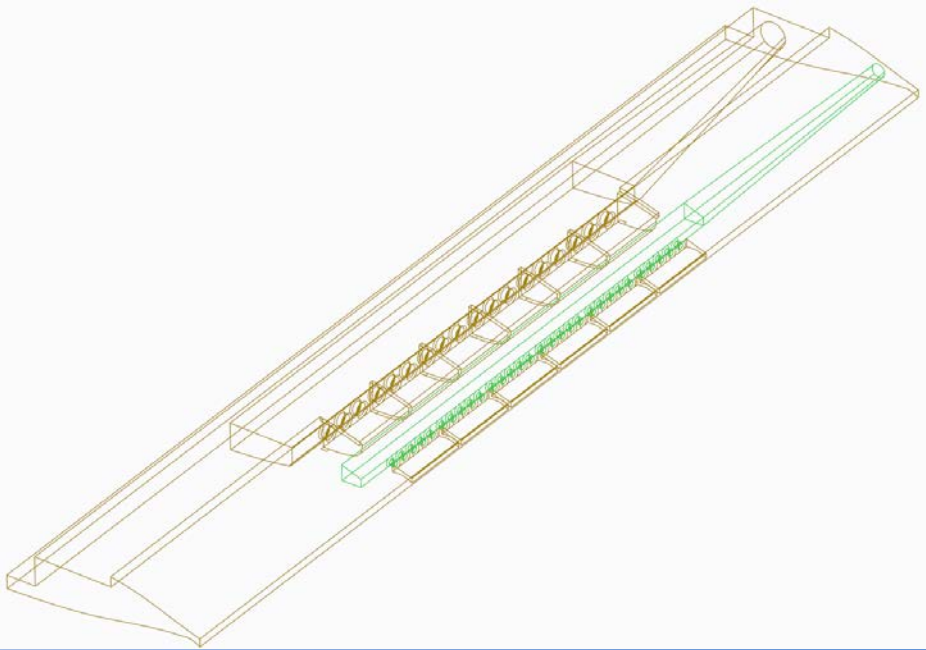




Wind Tunnel Model Design

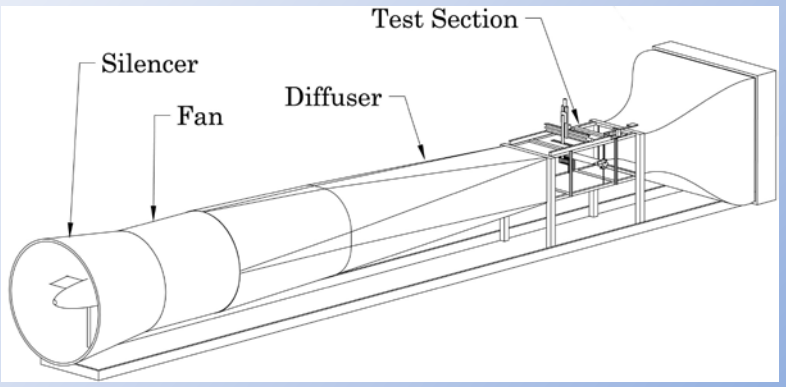
- Because of small scale, CFF flow is simulated





Low-Speed Wind Tunnel Test

- 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

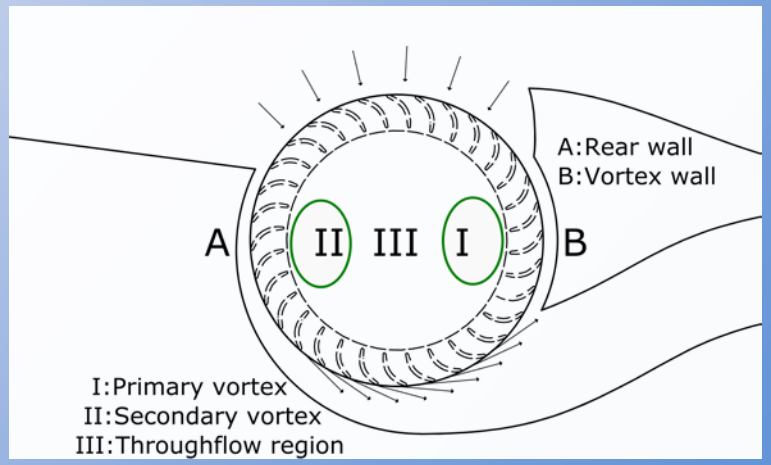


Cross-Flow Fan Overview

- 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

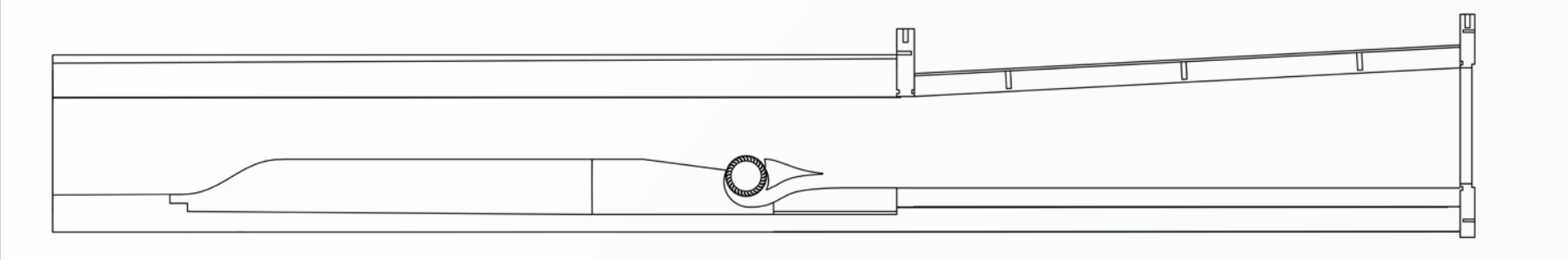
CFF Aerodynamics

- 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



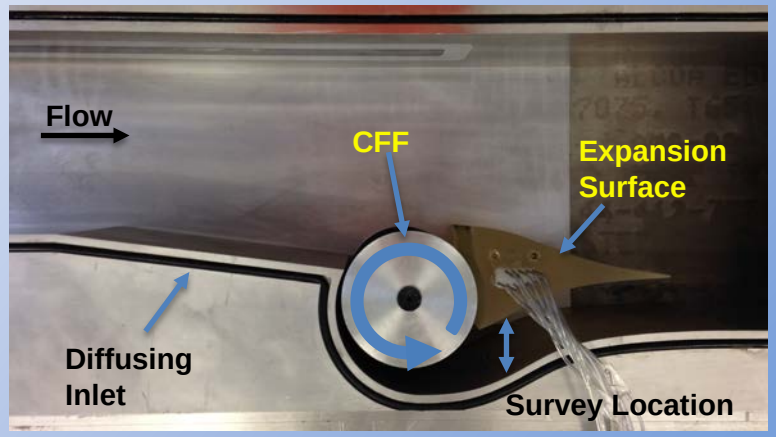
CFF Experimental Facility

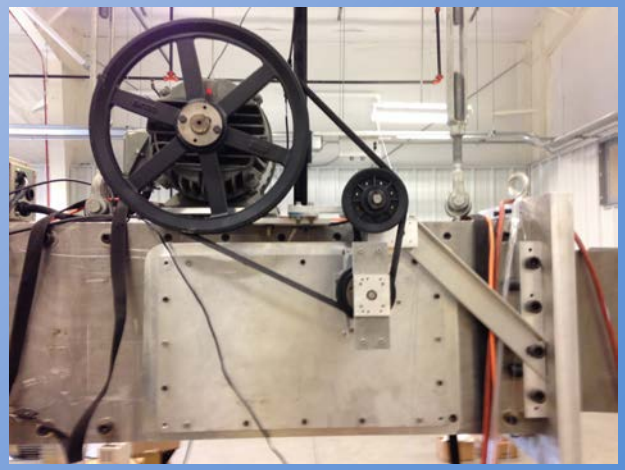
- Supersonic wind tunnel adapted for transonic flow
  - Blowdown-type configuration
  - New nozzle designed for subsonic flow
  - Test section machined to incorporate fan housing into tunnel wall
  - CFF spans tunnel, mounted with bearings in both of the tunnel walls



CFF Experiment Configuration

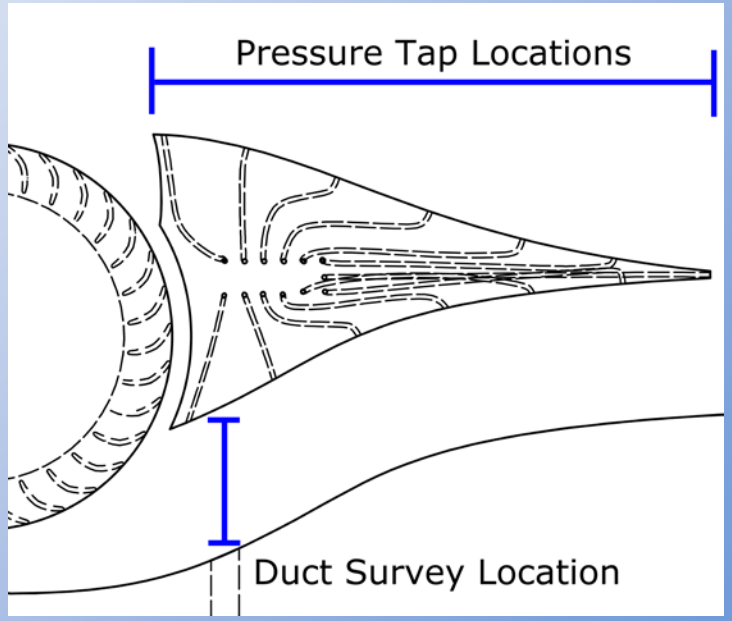
- Test section details
  - 3.4” diameter fan , 5” span
  - 7.5° diffusing inlet ramp for radial flow
  - Vortex wall/expansion surface manufactured with SLA printing
  - Probe survey location shown
- Fan driven by 3 hp motor
  - Pulley system designed for 3,000 to 15,000 RPM
  - Variable frequency AC Drive for control
  - 208 V power supply

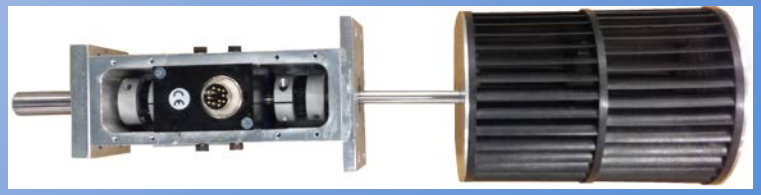




CFF Measurements

- 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

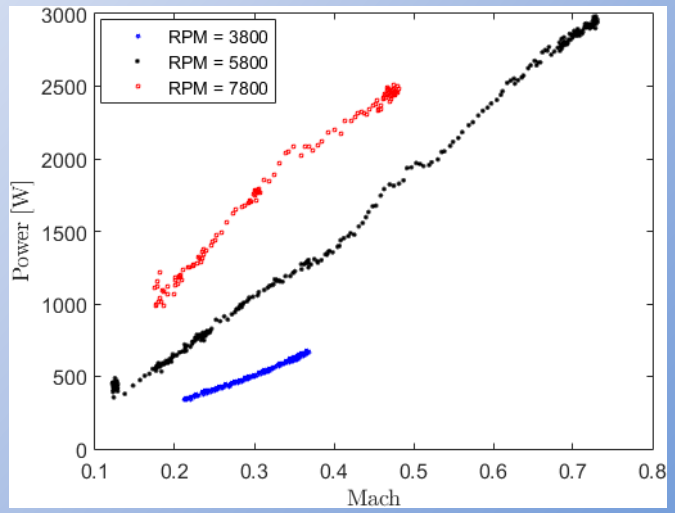


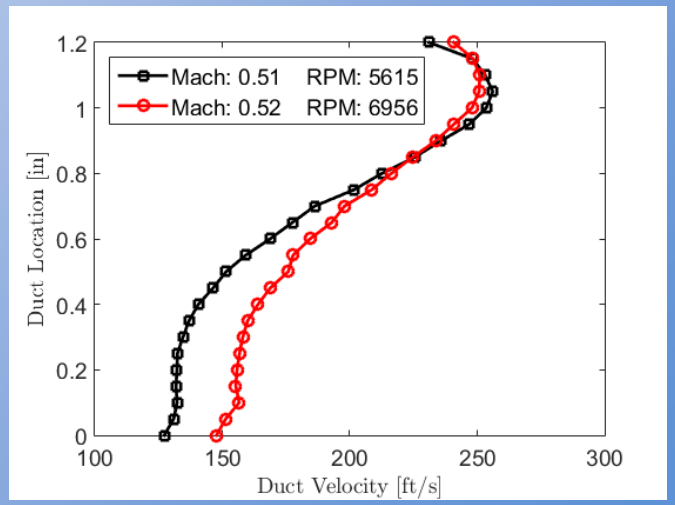


CFF Measurement Results

- Power Measurements
  - Fan power as f(M,RPM)
  - Data up to M = 0.73
- Duct Surveys
  - M = 0.4, 0.5, 0.6
  - RPM = 5500, 7000

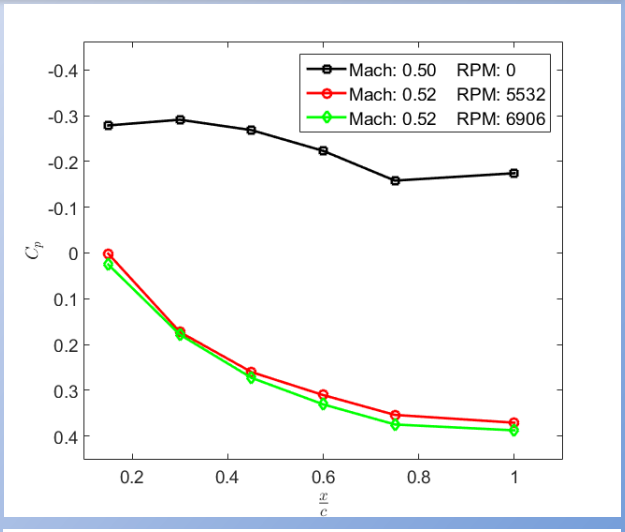
Mach	RPM	P_o (lbs/ft^2)	T_o (R)	V (ft/s)
0.41	5114.23	2066.33	516.81	168.27
0.41	5993.73	2072.46	526.65	178.75
0.52	5566.38	2035.77	521.13	182.26
0.52	6925.31	2059.63	537.05	194.68
0.59	5698.14	2021.91	525.51	196.41





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

$$P = 2\int_0^{B/2} \frac{W_s}{b} dy \quad \text{where } \frac{W_s}{b} = \frac{1}{2}\rho D_o U_o^3 \lambda$$

CFF Power Requirement

Pre-scaled test values

W_s [kW]	2.8808
b [ft]	0.4167
ρ [slug/ft³]	0.0021364
D_o [in]	3.457
U_o [ft/s]	85.395
λ	26.61
M	0.7014
RPM	5661.3

Scaled aircraft values

P [kW]	187.58
B [ft]	84.8
ρ [slug/ft³]	0.0005428
$D_{o,root}$ [in]	11.28
$D_{o,tip}$ [in]	4.94
U_o [ft/s]	76.8
M	0.7
RPM	Varies with D_o

- Calculation requires the assumption that the power coefficient λ 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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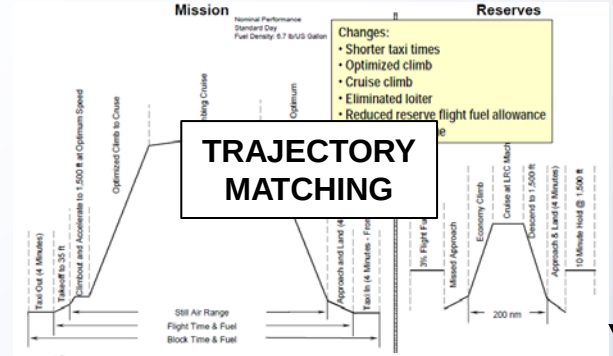
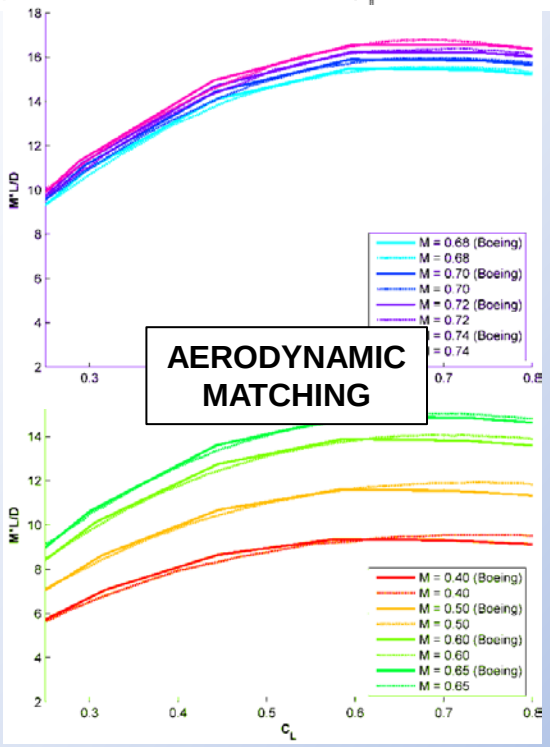


TRAJECTORY MATCHING



AERODYNAMIC MATCHING

GOALS

- **Understand the effects of the transonic Griffith/Goldschmeid airfoil via a systems-level analysis**

AVID ACS 5.04 (ACSYNT)

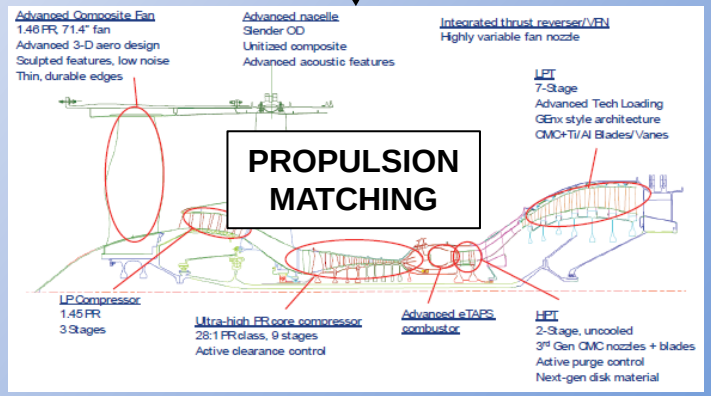
- Interdisciplinary aircraft synthesis program for conceptual design

N+4 SUGAR Refined

- 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**

GEOMETRY MATCHING

Trade Study: Aero, Propulsion, Weights



PROPULSION MATCHING

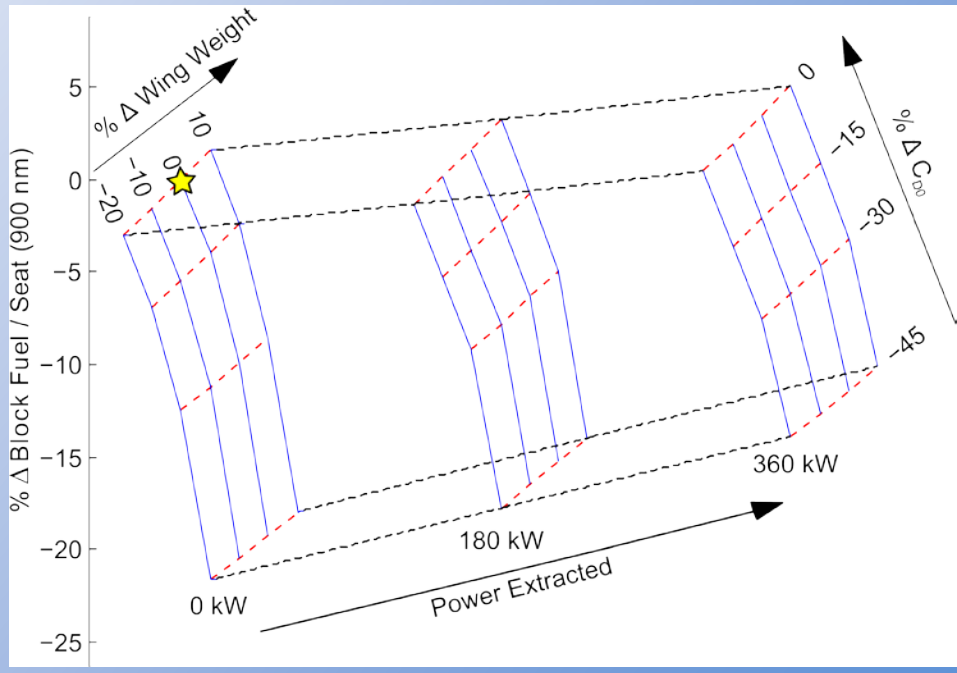
GROUP	WEIGHT (LB)	% TOGW
WING	13,780	10.1%
BENDING MATERIAL	5,754	4.2%
SPAR WEBS	994	0.7%
RIBS AND BULKHEADS	1,091	0.8%
AERODYNAMIC SURFACES	3,151	2.3%
SECONDARY STRUCTURE	2,791	2.0%
TAIL	2,676	2.0%
FUSELAGE	14,946	11.0%
LANDING GEAR	5,052	3.7%
NACELLE & PYLON	5,392	4.0%
PROPULSION	9,898	7.3%
ENGINES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

WEIGHT MATCHING

Preliminary Systems Analysis

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

$$\boldsymbol{C_{L_{a/c}} = C_{L_W} + \frac{S_{HT}}{S_W} C_{L_{HT}}}$$

$$C_{L_W} = (\alpha_{geo} - \boldsymbol{\alpha_{0lW}} + \boldsymbol{i_W}) C_{L_{W\alpha}}$$

$$C_{L_{HT}} = (\alpha_{geo} - \boldsymbol{\alpha_{0lHT}} + \boldsymbol{i_h} - \varepsilon_d) C_{L_{HT\alpha}}$$

$$\boldsymbol{C_{D_{ac}} = C_{D_W} + C_{D_{HT}} + C_{D_{rest}}}$$

$$C_{D_W} = C_{D_{Wmin}} + \boldsymbol{k_W} C_{L_W}^2 + \frac{{C_{L_W}}^2}{\pi e_W AR_W}$$

$$C_{D_{HT}} = C_{D_{HT0}} + \boldsymbol{k_{HT}} C_{L_{HT}}^2 + \frac{{C_{L_{HT}}}^2}{\pi e_{HT} AR_{HT}}$$

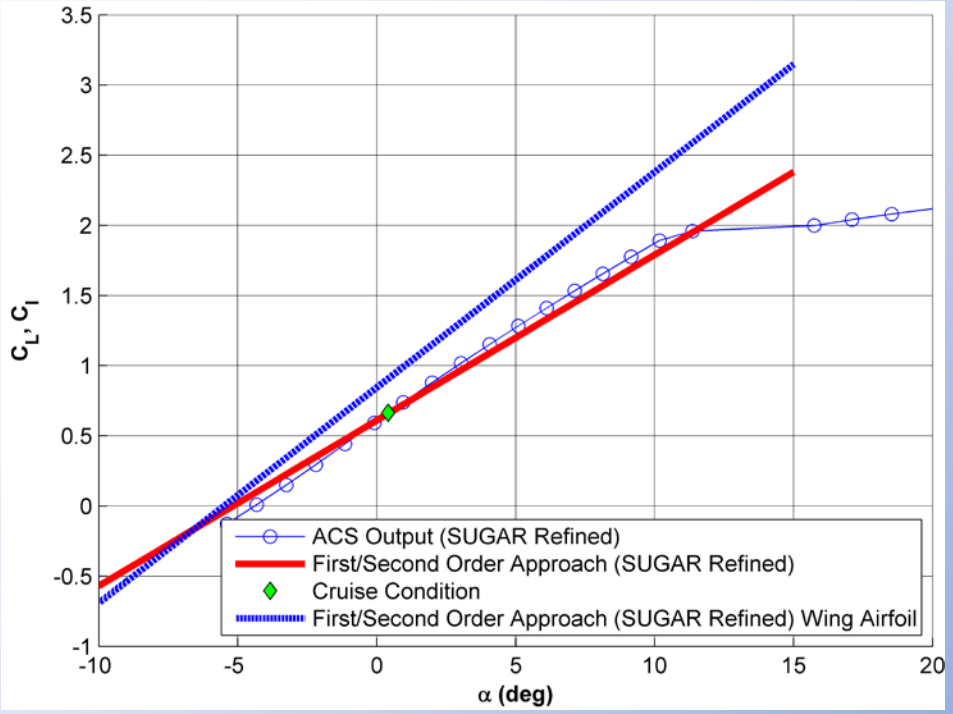
$$C_{D_{rest}} = C_{Df,body} + C_{Df,VT} + C_{Dinterference} + C_{Dwave} + C_{Dext}$$

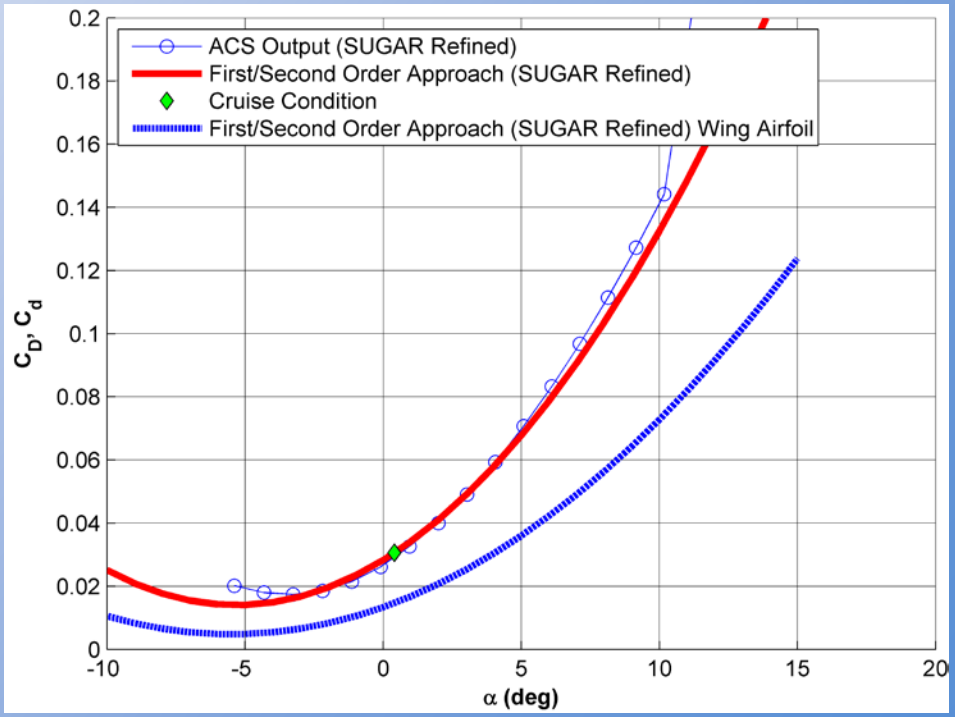
Aero Modeling (3)

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

$$C_{l_W} = \left(\alpha_{geo} - \boldsymbol{\alpha_{0l}} + \boldsymbol{i_W}\right)(m_0)_{M\neq 0}$$

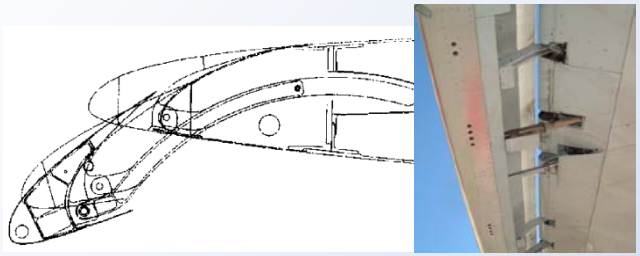
$$C_{d_W} = C_{D_{W0}} + \boldsymbol{k_W} C_{l_W}^2$$

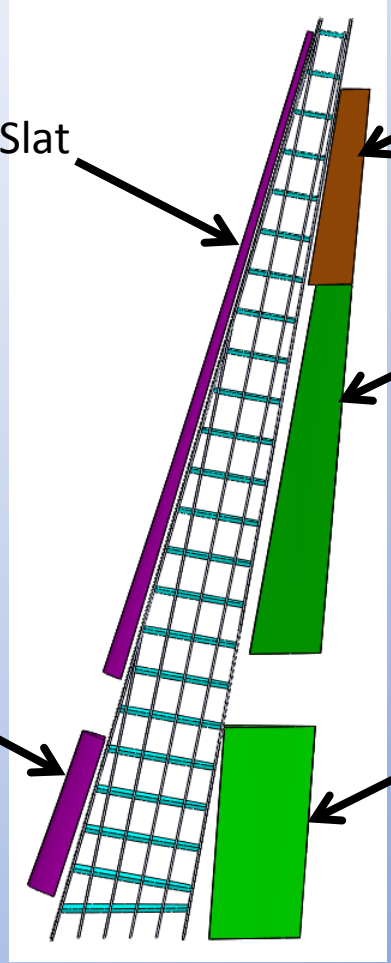


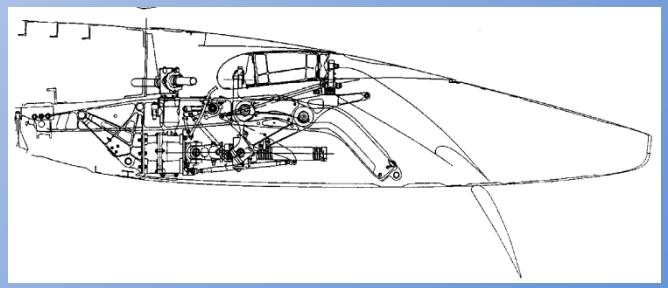


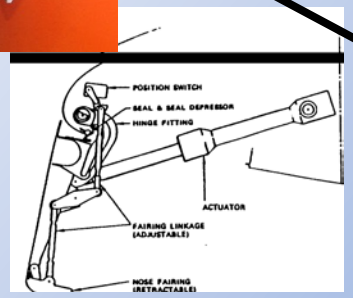
Aero Modeling (4)

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



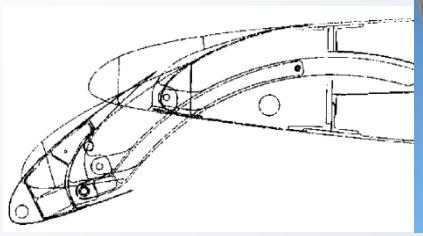


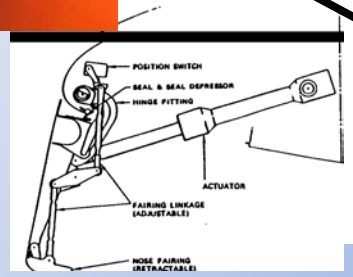


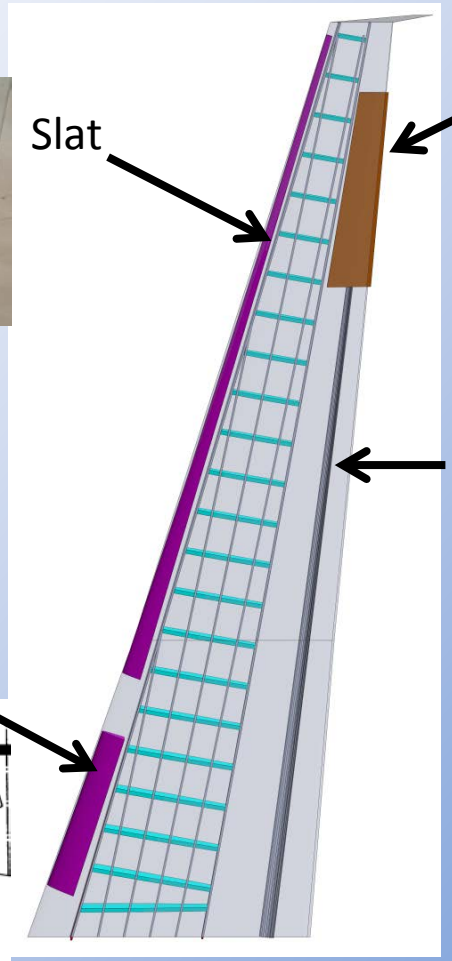


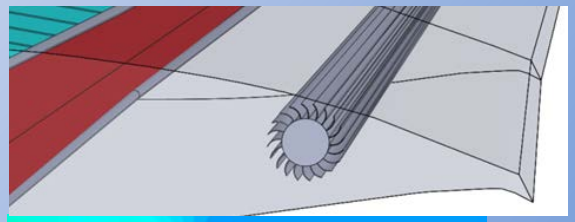
Aero Modeling (4)

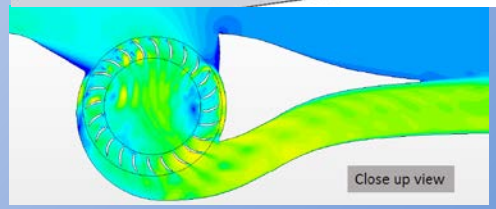
Wing CAD Model (OpenVSP/SolidWorks) – Boeing 737 NG wing design







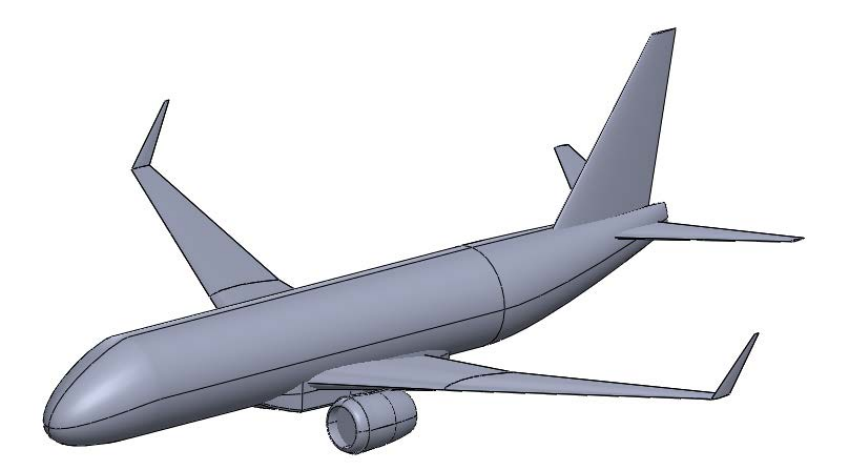


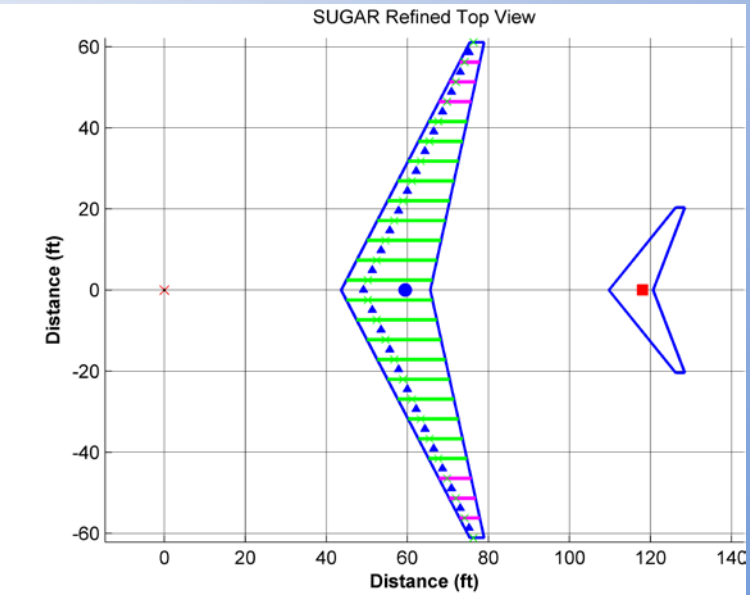


Crossflow Fan till Aileron (70-72% of span)

- 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

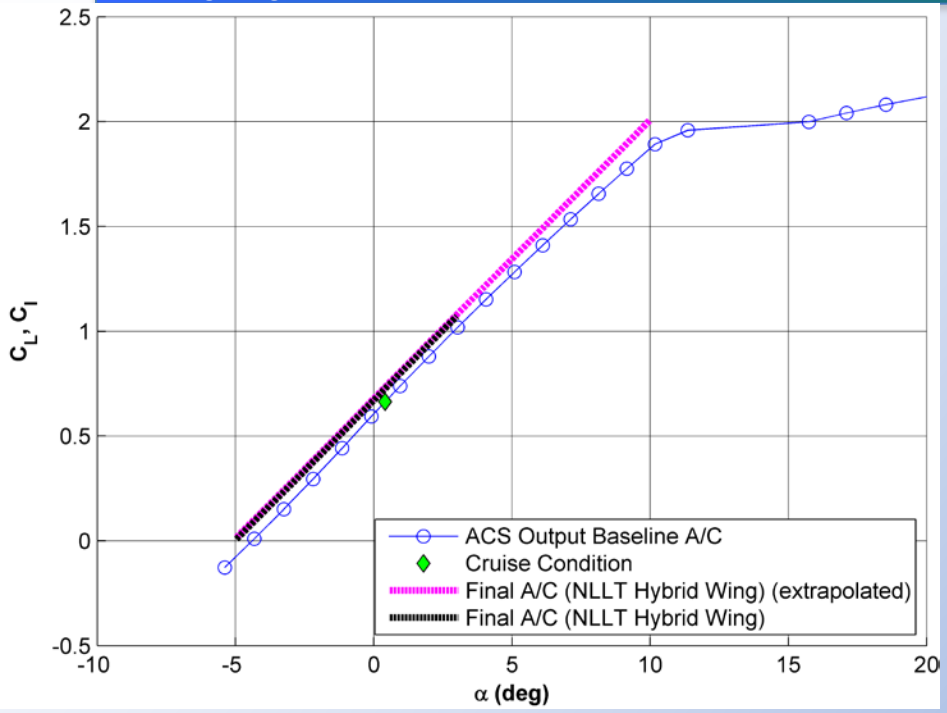
Aero Modeling (5)

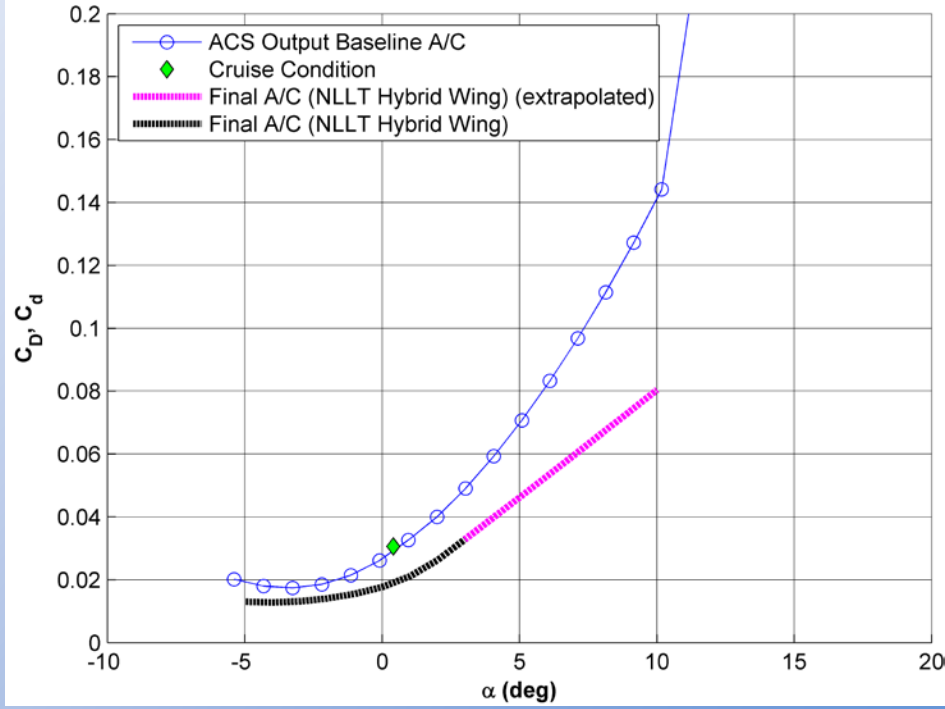




- Wing geometry transferred to MATLAB
- **Nonlinear lifting line theory** used to compute wing performance with varying spanwise airfoil distribution
- 70% of wing modeled uses **RHRC125.B1.M70** airfoil (green)
- 30% uses **first/second order approach** baseline wing airfoil (purple)

Aero Modeling (6)





- 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 → 45 kW → 56.3 kVA
    - Electric: 540 kVA
    - Crossflow Fan: 187.58 kW → 234.5 kVA
    - **Total Installed Aircraft Power: 830.8 kVA**

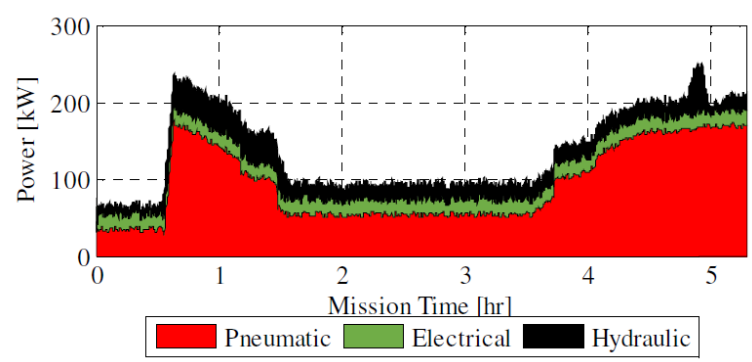


Figure 11. Instantaneous power consumption over a mission profile for a sample Boeing 737 model

Williams, M., et. al.,"PowerFlow: A Toolbox for Modeling and Simulation of Aircraft Systems", SAE 2015 AeroTech Congress & Exhibition, 2015-01-2417.

Weights Estimation (1)

- From Rudolph (Progress in Aerospace Sciences), 1996

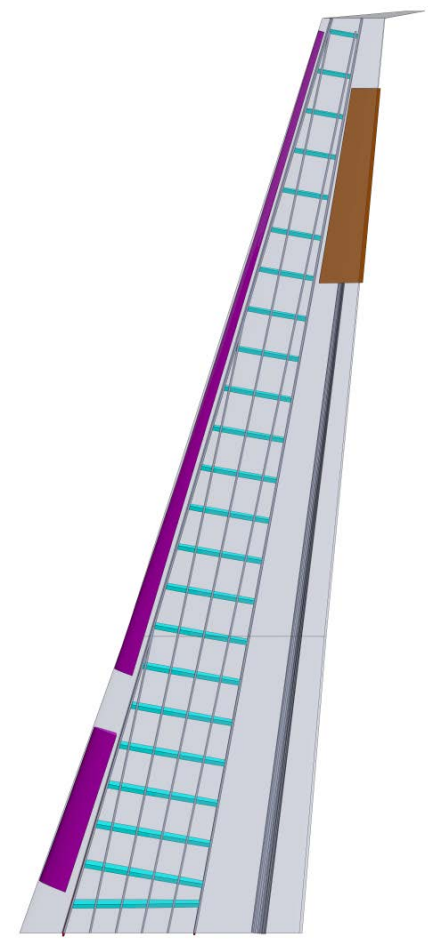


Table 4.1. Trailing-edge flap specific weights (weights in lb/ft^2 of stowed flap area)

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

Table 4.2. Specific weights for leading-edge devices (weights given in lb/ft^2)

	Type			
	Rigid Krueger	VC Krueger	Three-position slat with slave tracks	Three-position slat without slave tracks
Fixed leading edge	2.25	2.25	2.2	2.1
Moving panels	1.5	2.1	2.5	2.4
Actuation	1.5	1.75	1.3	1.3
Total flap	5.25	6.1	6.0	5.8

Weights Estimation (2)

Baseline

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

Final A/C

Remove inboard/outboard flap actuation and fairing → **- 683.1 lb (ΔW_{wing} = - 5 %)**

787 Architecture (4 IDG @ 250kVA each)
According to Kennett (1971) → 1.3 kVA/lb
Crossflow Requirement → + 180.4 lb

Crossflow Fan Motors (Green et. al. , 2012)
→ **$W_{motor} = 2.62 * P_{max}^{0.739}$ = + 148 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 lb

Block Fuel / Seat (900nm) = 37.28

% 11.8 reduction in fuel consumption

10% increase in wing weight → 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

- 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

Lift

$$C_{L_{ac}} = C_{L_W} + C_{L_{HT}}$$

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

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

- **To calculate** $C_{L\alpha}$

$$C_{l\alpha} = 2\pi = (m_0)_{M=0}$$

$$(m_0)_{M\neq 0} = \frac{(m_0)_{M=0}}{\sqrt{1-M^2}}$$ Compressibility corrections

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

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

$$C_{l_W} = (\alpha_{geo} - \alpha_{0l})\,(m_0)_{M\neq 0}$$

$$C_{l_{HT}} = (\alpha_{geo})\,(m_0)_{M\neq 0}$$

Drag

$$C_{D_{ac}} = C_{D_W} + C_{D_{HT}} + C_{D_{rest}}$$

$$C_{D_W} = C_{d_W} + \frac{{C_{LW}}^2}{\pi e AR}$$

$$C_{d_W} = C_{D_{0W}} + k_{visc1} {C_{l_W}}^2$$

$$C_{D_{HT}} = C_{d_HT} + \frac{{C_{LHT}}^2}{\pi e AR}$$

$$C_{d_HT} = C_{D_{0HT}} + k_{visc2} {C_{l_HT}}^2$$

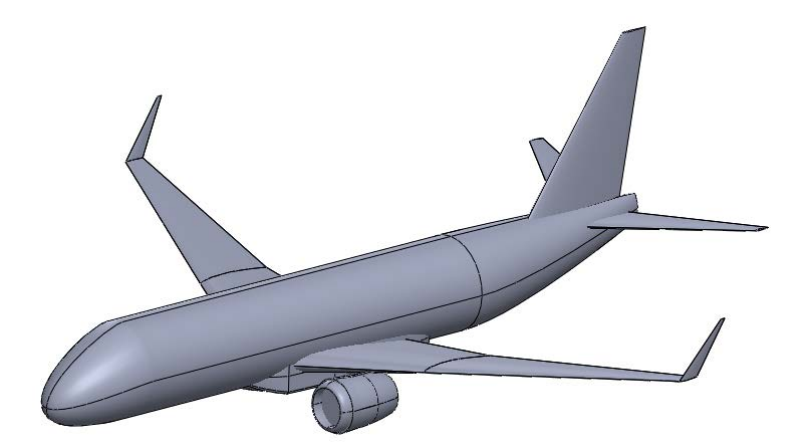
$$e = \frac{1}{1+\delta}$$

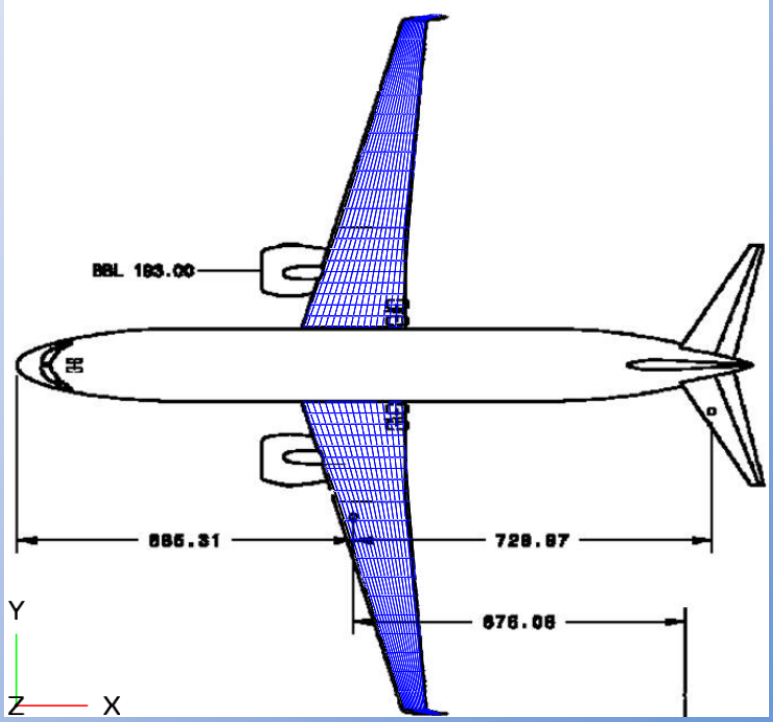
ROLLING HILLS RESEARCH CORPORATION

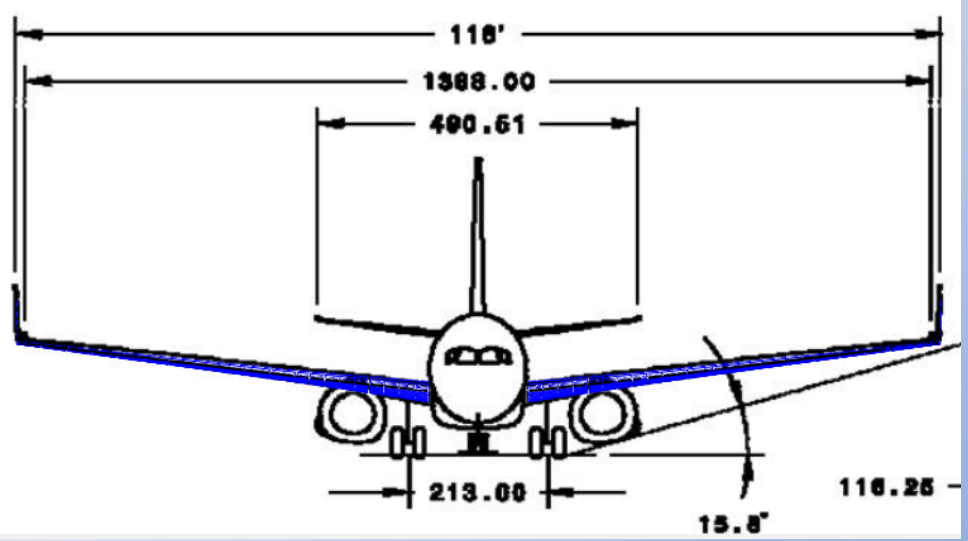
ILLINOIS

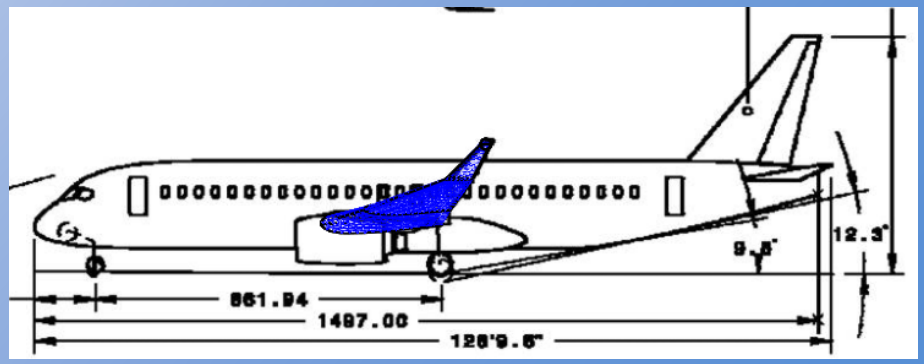
Wing Modeling

Leading Edge Aeronautics Research for NASA









February 16, 2016

Nonlinear Lifting Line

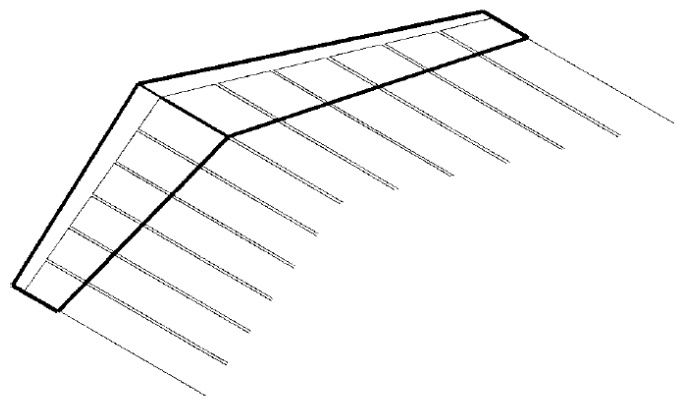
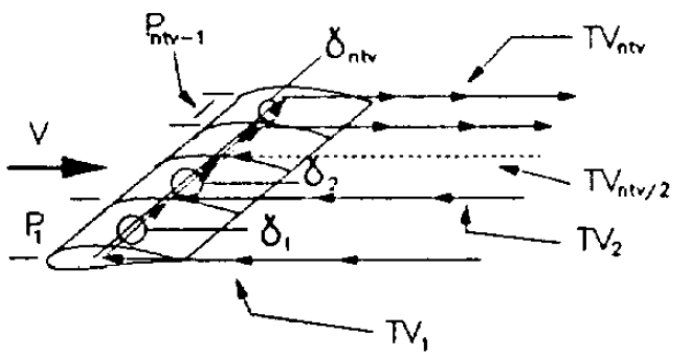


Fig. 1 Horseshoe vortices distributed along the quarter chord of a finite wing with sweep and dihedral.



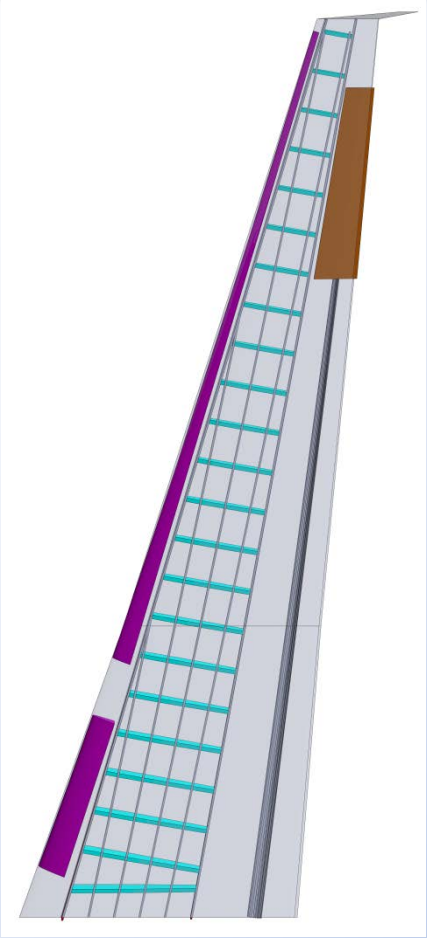
Spanwise Panels = 20
Spanwise Stations = 21

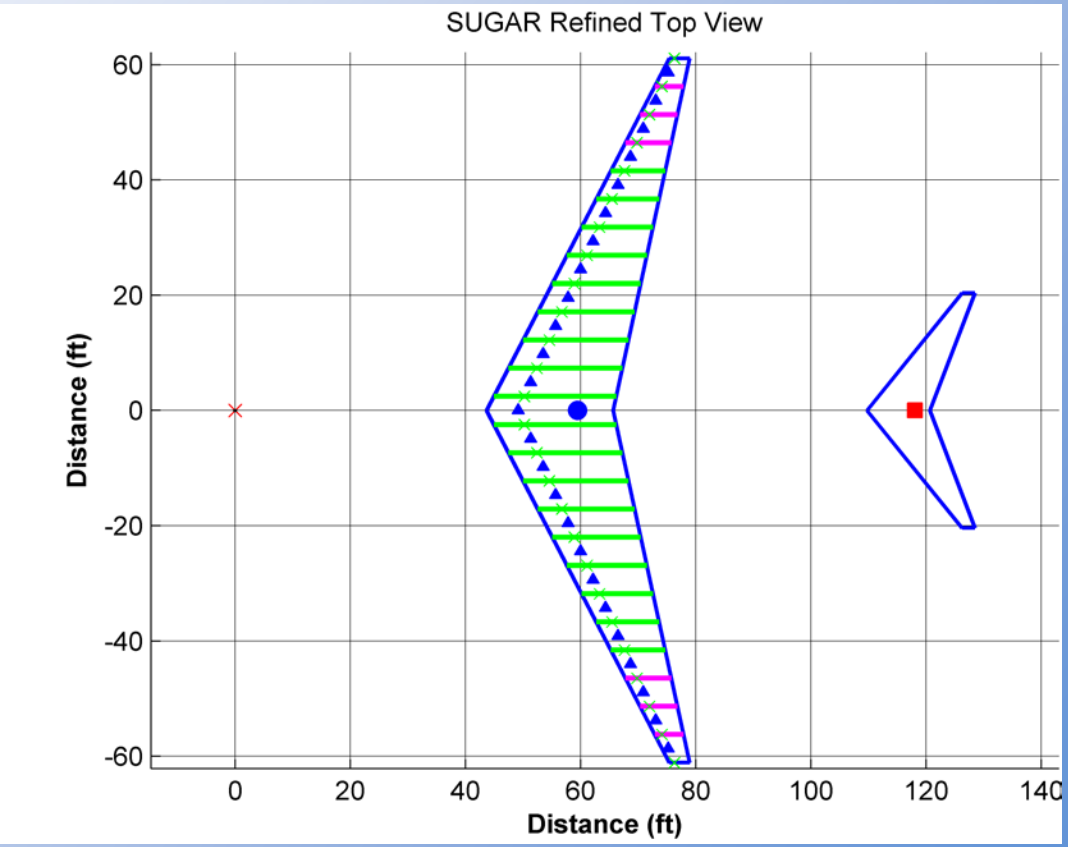
D (relaxation parameter) = 0.05
→ From Anderson

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





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