Technical Challenges to Systems Analysis and MDAO for Advanced Subsonic Transport Aircraft

AIAA Aerospace Sciences Meeting
January 9-12, 2012

William Haller and Mark Guynn
Technical Leads for Systems Analysis & Integration
Subsonic Fixed Wing Project
SFW Strategic Thrusts & Technical Challenges

Energy Efficiency Thrust *(with emphasis on N+3)*
Develop economically practical approaches to improve aircraft efficiency

Environmental Compatibility Thrust *(with emphasis on N+3)*
Develop economically practical approaches to minimize environmental impact

Cross-Cutting Challenge *(pervasive across generations)*

TC1 - Reduce aircraft drag with minimal impact on weight (aerodynamic efficiency)

TC2 - Reduce aircraft operating empty weight with minimal impact on drag (structural efficiency)

TC3 - Reduce thrust-specific energy consumption while minimizing cross-disciplinary impacts (propulsion efficiency)

TC4 - Reduce harmful emissions attributable to aircraft energy consumption

TC5 - Reduce perceived community noise attributable to aircraft with minimal impact on weight and performance

TC6 - Revolutionary tools and methods enabling practical design, analysis, optimization, & validation of technology solutions for vehicle system energy efficiency & environmental compatibility

Energy & Environment

- Direct Impact
- Indirect Impact

Economically Viable
Maintain Safety

Enable Advanced Operations

Revolutionary Tools and Methods
### NASA Subsonic Transport System Level Metrics

*...technology for dramatically improving noise, emissions, & performance*

<table>
<thead>
<tr>
<th>TECHNOLOGY BENEFITS*</th>
<th>TECHNOLOGY GENERATIONS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Technology Readiness Level = 4-6)</td>
<td></td>
</tr>
<tr>
<td>Noise (cum margin rel. to Stage 4)</td>
<td>-32 dB</td>
<td>-42 dB</td>
</tr>
<tr>
<td>LTO NOx Emissions (rel. to CAEP 6)</td>
<td>-60%</td>
<td>-75%</td>
</tr>
<tr>
<td>Cruise NOx Emissions (rel. to 2005 best in class)</td>
<td>-55%</td>
<td>-70%</td>
</tr>
<tr>
<td>Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)</td>
<td>-33%</td>
<td>-50%</td>
</tr>
</tbody>
</table>

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO₂ emission benefits dependent on life-cycle CO₂ per MJ for fuel and/or energy source used
**Diversified Portfolio Addressing N+3 Goals**

Broadly applicable subsystems and enabling technologies

### N+3 Vehicle Concepts

- Active Flow Control
- Tailored Load Path Structure

### N+3 Subsystem Concepts

- Tailored Fuselage
- High AR Elastic Wing
- Quiet, Simplified High-Lift
- High Eff. Small Gas Generator
- Hybrid Electric Propulsion
- Propulsion Airframe Integration
- Alternative Fuels

### Technical Areas

**Drag**
- Turbulent CF Drag Reduction
- Active Flow Control
- Crankshaft Emissions

**Weight**
- Tailored Load Path Structure
- Tailored Load Path Structure

**TSEC**
- Designer Materials
- Elastic Aircraft Flight Control

**Clean**
- Aerodynamic Shaping
- High-Lift System Noise

**Noise**
- Landing Gear Noise
- Decentralized Control
- Fuel-Efficient Combustion

**Tools**
- MDMA, System Modeling, Physics-Based Tools

### Tool Box

<table>
<thead>
<tr>
<th>Structure/Aeroelastic/Materials</th>
<th>Aerodynamics</th>
<th>Acoustics</th>
<th>Combustion</th>
<th>Propulsion</th>
<th>MDAO</th>
<th>Systems Analysis/Conceptual Design</th>
</tr>
</thead>
</table>

**Subsonic Fixed Wing Project**

Fundamental Aeronautics

Active Flow Control

Tailored Load Path Structure

Materials

Turbulent CF Drag Reduction

Hot Section Materials

Tip/Endwall Aerodynamics

Decentralized Control

Fuel-Flexible Combustion

Core Noise

Gas-Turbine/Electric Hybrids

Transmission and Winding Materials

Aircraft Power Distribution

Adaptive, Lt Wt Fan Structure

Distortion Tolerant Fan

Acoustic Liners

Propulsion Airframe Aeroacoustics

Emission & Performance

Clean Weight Drag Noise Tools
Diversified Portfolio Addressing N+3 Goals broadly applicable subsystems and enabling technologies

N+3 Vehicle Concepts

N+3 Subsystem Concepts

Technical Areas

<table>
<thead>
<tr>
<th>Drag</th>
<th>TSEC</th>
<th>Clean</th>
<th>Noise</th>
<th>Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulent CF Drag Reduction</td>
<td>Turbulent CF Drag Reduction</td>
<td>Turbulent CF Drag Reduction</td>
<td>Turbulent CF Drag Reduction</td>
<td>Turbulent CF Drag Reduction</td>
</tr>
<tr>
<td>Active Flow Control</td>
<td>Active Flow Control</td>
<td>Active Flow Control</td>
<td>Active Flow Control</td>
<td>Active Flow Control</td>
</tr>
<tr>
<td>Quiet, Simplified High-Lift</td>
<td>Quiet, Simplified High-Lift</td>
<td>Quiet, Simplified High-Lift</td>
<td>Quiet, Simplified High-Lift</td>
<td>Quiet, Simplified High-Lift</td>
</tr>
<tr>
<td>In Eff. Small Gas Generator</td>
<td>In Eff. Small Gas Generator</td>
<td>In Eff. Small Gas Generator</td>
<td>In Eff. Small Gas Generator</td>
<td>In Eff. Small Gas Generator</td>
</tr>
<tr>
<td>Hybrid Electric Propulsion</td>
<td>Hybrid Electric Propulsion</td>
<td>Hybrid Electric Propulsion</td>
<td>Hybrid Electric Propulsion</td>
<td>Hybrid Electric Propulsion</td>
</tr>
<tr>
<td>Propulsion Airframe Integration</td>
<td>Propulsion Airframe Integration</td>
<td>Propulsion Airframe Integration</td>
<td>Propulsion Airframe Integration</td>
<td>Propulsion Airframe Integration</td>
</tr>
<tr>
<td>Alternative Fuels</td>
<td>Alternative Fuels</td>
<td>Alternative Fuels</td>
<td>Alternative Fuels</td>
<td>Alternative Fuels</td>
</tr>
</tbody>
</table>

Vehicle/Propulsion Assessments

SA&I Primary Focus Areas

Enhanced Tools & Methods

Tool Box – MDAO, System Modeling, Physics-Based Tools

<table>
<thead>
<tr>
<th>Structure/Aeroelastic/Materials</th>
<th>Aerodynamics</th>
<th>Acoustics</th>
<th>Combustion</th>
<th>Propulsion</th>
</tr>
</thead>
</table>
Envisioned Challenges – NASA Perspective

Systems Analysis/Conceptual Design Tools & Methods:
- Analyzing advanced/unconventional configurations using empirical-based prediction methods (conventional architectures)
- Limited/no uncertainty quantification
- Development of rapid turnaround, physics-based design/analysis tools
- Increased analysis efficiency – more accuracy with less time & effort
- Greater automation with intelligent streamlining of design process

MDAO Tools & Methods:
- Establishing standard interfaces between discipline tools
- Lack of mid-fidelity codes to bridge gap between low & high fidelity
- High computational costs for hi-fidelity tools limit number of function evaluations
- Optimization performance comparisons based on standardized test problem set
- Difficulty w/interfacing analysis environments to commercial CAD tools
- Common (tool independent) geometry interface to build analysis tools around
- Transition between multiple geometry engines as design process progresses
Moving Forward

• Over the past 6-9 months, SFW has identified technical challenges and then developed a strategic framework and tactical plans to guide project going forward

• In support of the project’s objectives, Systems Analysis & Integration (SA&I) has several responsibilities:
  – Lead MDAO engineering framework development efforts
  – Develop new/enhanced conceptual design tools & methods
  – Conduct SFW’s technology assessments

• Therefore, the sub-project structure consists of 3 critical elements
  – MDAO Tools & Methods
  – Systems Analysis/Conceptual Design Tools & Methods
  – Advanced Concepts: Modeling, Studies & Assessments
**MDAO Tools & Methods**

**Focus:** Develop an advanced, open source MDAO framework enabling the integration of multi-fidelity, multi-disciplinary design and analysis tools

**Technical Content:**

*Open Source Framework Development (OpenMDAO):* Continue development of open-source, Python-based multi-disciplinary engineering framework leading to initial “full” release (V1.0)

*Geometry Development:* NRA-led activity focused on the development of a geometry handling capability within the OpenMDAO framework. (NRA participants – MIT & University of Michigan)

*MDAO Evaluation/Test Problem Formulation:* Exercise existing OpenMDAO integration capabilities through a series of aerospace related test problems, included herein will be combustion & structure related activities

*GEN2 MDAO Framework Validation:* Validation of ModelCenter-based framework by assessing predictive capability of integrated set of design/analysis tools on state-of-the-art commercial transport (B787)
Sample of MDAO Tools & Methods Work (1)

GEN2 MDAO Tool Suite Validation
- 2\textsuperscript{nd} generation capability developed primarily to analyze unconventional systems
- Validation completed by comparing aircraft weight/performance for both configurations against independent data sources
- Predicted values met, or nearly met, accuracy targets for all metrics for both architectures

<table>
<thead>
<tr>
<th>Metric</th>
<th>Conventional</th>
<th>Goal</th>
<th>Unconventional</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff Gross Weight</td>
<td>-3.1% ± 5%</td>
<td>+2.0% ± 15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>-0.1% ± 2.5%</td>
<td>-1.2% ± 10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Takeoff Field Length</td>
<td>-4.2% ± 5%</td>
<td>+7.1% ± 15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landing Field Length</td>
<td>+2.3% ± 5%</td>
<td>+10.7% ± 15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LTO NOx</td>
<td>-5.8% ± 5%</td>
<td>No Validation Data ± 15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg EPNL</td>
<td>+2.1 dB ± 2.5 dB</td>
<td>No Validation Data ± 7.5 dB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Comparison of Prediction vs. Available Data
Sample of MDAO Tools & Methods Work (2)

OpenMDAO Application Problem – Lean Direct Injection Combustor
- Develop parametric-CAD approach for LDI combustor design
- Quantify influence of key aerothermodynamic variables on individual & coupled injector performance
- Investigate parametric-CAD approach to Hi-Fidelity (CFD) design-by-analysis addressing issues of geometry handling, automated meshing and Low/Hi-fidelity code coupling

Flow Diagram of Envisioned Process
Focus: Develop higher order design and analysis methods that enable reliable and robust exploration of conventional and unconventional concepts

Technical Content:
Robust Parametric Geometry Tools: Develop robust parametric geometry tools to achieve the best conceptual design capability and foster/improve the geometric tools internally to insure functionality to maximize tool effectiveness. (NRA participants – Cal Poly-SLO & Georgia Tech)

Physics-Based Aerodynamic Design: Develop physics-based laminar flow/drag prediction tool that can be used in conceptual design process; investigate use of higher-order analysis methods to enable high-lift prediction tools suitable for system analysis/conceptual design.

Weight Prediction Enhancements: Develop process to bridge gap between conflicting requirements for quick concept development/evaluation and need for design detail to support high-fidelity analysis enabling integration of higher fidelity structural analysis into the conceptual design environment.

Physics-Based Aeromechanical Design: Enhance current engine flowpath/weight estimation tool (WATE++) by creating new modules that will represent some of components envisioned for N+3 (e.g., turbo-electric).

High-Fidelity MDAO for Highly Integrated Propulsion/Airframe: Develop quantitatively reliable/computationally efficient high-fidelity MDAO predictive capability for next generations of highly integrated propulsion & airframe configurations.
High Fidelity MDAO for Highly Integrated Propulsion/Airframe

- CFD simulation of the HWB configuration with embedded engines (N2B)
- Provide aerodynamic characteristics of the complete configuration assessing the impact on propulsion system performance (incl. Boundary Layer Ingestion)
- Design optimization for
  ✓ BLI inlet distortion/total pressure recovery
  ✓ Integrated airframe-nacelle configuration
Advanced Concepts

Focus: Model/assess advanced propulsion and airframe technologies to advance knowledge and understanding of a diverse collection of airliner concepts that move beyond the conventional vehicles of today

Technical Content:
SUGAR Phase II NRA Collaboration: Work in concert with NRA partners (Boeing, GE Aviation, VA Tech & GA Tech) to understand/independently assess N+4 reference and advanced technology concepts. In addition, provide an independent assessment of N+3 refined Truss-Braced Wing concepts and hybrid electric concepts.

Turbo-electric Distributed Propulsion: Enhance NASA’s Turbo-electric Distributed Propulsion concept (N3-X) through further refinement of current in-house models to increase confidence of fuel burn reduction potential; in addition, perform acoustic and NO\textsubscript{X} emission assessments.

Open Rotor Integration Study: Enhance current open rotor assessment through high-fidelity modeling capability to improve understanding of installation effects on open rotor performance.

Conceptual Assessment of Pressure Gain Combustion: Perform conceptual level assessment of the potential benefits, and technology challenges, of pressure gain combustion for commercial transport engines.
Advanced Concept Work – Open Rotor

- SFW has been conducting an on-going engine trade study to assess propulsion options for advanced single-aisle (737/A320 class) aircraft
  - Initial focus on ultra-high bypass ratio (UHB) turbofan concepts, followed by investigation of open-rotor engine architectures
  - Multiple interactions with industry over the years to obtain feedback
  - Numerous technical reports and conference papers produced, plus 1 journal article

- Recently completed assessment of open rotor concept
  - Collaborative effort (w/GE) utilizing modern blade set performance/aero
  - Initial comparison of fuel burn/noise delta vs. geared turbofan
  - Technical report/conference paper detailing results planned for 2012
NASA Study Results – Fuel Burn vs. Noise
162 Pax Airplane w/3250 nm design mission – $M_{cr} = 0.78$

Baseline airplane:
“stretched, aero updated” MD90-30

% Fuel Burn Benefit

Noise Margin

~9% Fuel Burn

~12 dB

N+1 Tech
UHB TF
BPR ~14

N+1 Tech
Open Rotor
BPR >30
Advanced Concept Work – TeDP

- Study conducted to compare potential of turbo-electric distributed propulsion (TeDP) on HWB architecture
- Variants created (LH$_2$-cooled & podded TF) for comparison
- Preliminary fuel burn estimates tentatively meet N+3 goal but warrants further detail design analysis
- Next step involves investigation of concept’s acoustic & emission potential
• SFW has identified technical challenges and developed strategic framework and tactical plans to guide project going forward
• The project has created a diversified portfolio of technologies, with focus primarily (but not exclusively) in the N+3 timeframe
• Systems Analysis & Integration (SA&I) support centered in 3 areas:
  – MDAO engineering framework development effort
  – Systems Analysis/Conceptual Design Tool & Methods Development
  – Vehicle/Propulsion Assessments
• The sub-project is divided into 3 elements to address work:
  – MDAO Tools & Methods
  – Systems Analysis/Conceptual Design Tools & Methods
  – Advanced Concepts: Modeling, Studies & Assessments
• Requisite work defined to address technical challenges
• Several examples of recent accomplishments detailed
Rationale for Working Tools & Methods Development

What are we trying to do?
• Improve the ability to assess the performance, environmental compatibility, and risk of conventional and unconventional aircraft configurations and advanced technologies

Why?
• Lack of robust, reliable capability to accurately design/assess unconventional technologies/concepts is an obstacle to revolutionary changes in current design paradigms
• NASA needs ability to be an honest broker regarding the claimed advantages of unconventional configurations and advanced technologies
• Better tools will foster greater creativity and innovation in aircraft design

How is it done today, and what are the limits of current practice?
• Use of lower order methods limits ability to accurately model new configurations/technologies
• Successful use of higher order methods requires details not normally available in early design phases
• Proprietary COTS MDAO frameworks make it difficult for outside developers to integrate new capabilities directly into architecture

What is new in our approach?
• Interjection of more physics into conceptual design process with focus on bridging the gap between high order analysis and high order design capabilities
• Open source framework using Python programming language, enabling new tools to be constructed natively in framework
• Open source licensing enables collaboration across MDAO community

What are the payoffs if successful?
• Broad opportunities for contributions from external MDAO researchers and greatly expanded capability for MDAO users
• Ability to investigate new, innovative concepts with higher degree of confidence
• Better informed decisions regarding investment in unconventional concepts and technologies