Multidisciplinary Design Optimization of Low-Airframe-Noise Transport Aircraft

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Outline

◆ Introduction
◆ Research objectives
◆ Methodology
◆ MDO formulation
◆ Design studies
◆ Conclusions
◆ Future work

(Source: www.airliners.net)
Aircraft noise is a growing problem

- 100% increase in noise related restrictions in the last decade
- NASA’s goal is to reduce noise by 20 decibels in next 20 years

(Data from “Advisory Circular”, DOT, FAA, November 2001)
Aircraft must be certified by the FAA and ICAO in terms of noise levels.

Certification noise is measured at flyover, sideline, and approach.

Based on aircraft max $TOGW$ and number of engines, the noise level is limited.

Additionally, regulations limit the hours and the number of operations.
Research Objectives

- Include aircraft noise in the conceptual design phase
- Design *low-airframe-noise* transport aircraft using MDO
- Quantify change in performance w.r.t. traditionally designed aircraft

Airframe Noise Sources
Design Methodology: Noise as a Design Constraint

- Optimize aircraft without considering aircraft noise
- Aircraft noise analysis of reference configuration
- Add a noise constraint
- Re-optimize the reference configuration for a target noise reduction

Reference configuration

Reference noise level, $N_{ref}$

$N_{new} - N_{ref} \leq \Delta N$

New configuration with $\Delta N$ less noise
Aircraft analysis codes previously developed at Virginia Tech
  – High-lift system analysis module was added

ANOPP used for aircraft noise analysis

ModelCenter used to integrate the codes

DOT is the optimizer; Method of Feasible Directions optimization algorithm
ANOPP Overview

- Semi-empirical code
- Uses publicly available noise prediction schemes
- Continuously updated by NASA
- The airframe noise module is component based
- Based on airframe noise models by Fink
- The general approach:

\[
\langle p^2 \rangle = \frac{\Pi}{4 \pi r_s^2} \frac{D(\theta, \phi)F(S)}{(1 - M_\infty \cos \theta)^4}
\]

\[
\Pi = K (M_\infty)^a G
\]
ANOPP – Acoustic Power of Each Component

- **Wing Trailing-Edge (Clean wing)**

  \[ \Pi_{\text{Wing TE}} = K_1 (M_\infty)^5 \delta_w \]

- **Leading-Edge Slat**
  - Increment on wing TE noise
  - TE noise of LE slat

- **Trailing-Edge Flap**

  \[ \Pi_{\text{Flap}} = K_2 (M_\infty)^6 S_f \sin^2 \delta_f \]

- **Landing-Gear**

  \[ \Pi_{\text{Landing gear strut}} = K_3 (M_\infty)^6 d l \]

  \[ \Pi_{\text{Landing gear wheels}} = K_4 (M_\infty)^6 d^2 n \]

\[ \delta_w = 0.37 S_w \left( \frac{\rho_\infty M_\infty c_\infty S_w}{\mu_\infty b_w} \right)^{-0.2} \]
MDO Formulation

- Objective function
  - Min Takeoff Gross Weight

- Design variables (17-22)
  - Geometry
  - Average Cruise Altitude
  - Sea level static thrust
  - Fuel weight

- Constraints (16-17)
  - Geometry
  - Performance
    - Takeoff, Climb, Cruise, Landing

- Parameters
  - Fuselage geometry
High-Lift System Configuration

Planform View

- High-lift analysis model based on semi-empirical methods by Torenbeek
- Model validated by analyzing a DC-9-30 and comparing with published data
High-Lift Design Limits and Requirements

\[ \alpha_{\text{limit}} = \theta_{ts} - \gamma_{gs} \]

FAA Design Requirement: \( C_{L_{\text{max}}} \geq 1.3^2 C_{L_{\text{app}}} \)
MDO Formulation for the High-Lift System

MDO

DV’s: \( b_f/2 \), \( E_f \)

Constraints:

\[
C_{L_{\text{max}}} \geq 1.3^2 C_{L_{\text{app}}}
\]

\[
C_{L_{\text{max}}} \leq C_{L_{\text{max\,limit}}}
\]

\[
\alpha_{\text{app}} \leq \alpha_{\text{tailscrape}} - \gamma_{\text{glideslope}} = 15 \text{ deg}
\]

\[
\eta_{f_o} \leq 0.75
\]

Flap Deflection:

\[
\min_{0 \leq \delta_f \leq 30} \left| 1.3^2 C_{L_{\text{app}}} - C_{L_{\text{max}}} \left( \delta_f \right) \right|
\]

Side Constraint: \( 0 \leq b_f/2 \leq 80 \text{ ft} \)

Parameters: \( C_{L_{\text{max\,limit}}} \), \( V_{\text{app}} \), \( E_a \), \( E_s \)
Design Studies

1. Approach speed study
2. TE flap noise reduction
3. Airframe noise analysis of cantilever wing vs. SBW
Study 1: Approach Speed Study
Reducing airframe noise by reducing approach speed alone, will not provide significant noise reduction without a large weight penalty.
Study 2: TE flap noise reduction
Eliminate TE flaps by increasing $S_{\text{ref}}$ and $\alpha$ without incurring significant weight penalty.
Thus, eliminating any noise associated with TE flaps
Study 3: Airframe noise analysis of cantilever wing and SBW
SBW shows a significant improvement in weight & performance compared to a cantilever wing.

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Cantilever Wing</th>
<th>SBW</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOGW (lb)</td>
<td>601,901</td>
<td>543,066</td>
<td>-9.8%</td>
</tr>
<tr>
<td>Fuel Weight (lb)</td>
<td>230,614</td>
<td>196,236</td>
<td>-14.9%</td>
</tr>
<tr>
<td>Wing Weight (lb)</td>
<td>90,044</td>
<td>81,492</td>
<td>-9.5%</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>9.91</td>
<td>11.42</td>
<td>15.2%</td>
</tr>
<tr>
<td>L/D at Cruise</td>
<td>21.14</td>
<td>23.54</td>
<td>11.4%</td>
</tr>
<tr>
<td>Specific Range (nm/1000 lb fuel)</td>
<td>31.25</td>
<td>37.59</td>
<td>20.3%</td>
</tr>
</tbody>
</table>

\[ \alpha_{\text{app}} = 7.7^\circ, \ \delta_f = 30^\circ \]

\[ \alpha_{\text{app}} = 5.8^\circ, \ \delta_f = 30^\circ \]
SBW has a similar or potentially lower total airframe noise than a cantilever wing aircraft

<table>
<thead>
<tr>
<th>Component</th>
<th>Cantilever Wing (EPNdB)</th>
<th>SBW (EPNdB)</th>
<th>Difference (EPNdB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Landing Gear</td>
<td>87.02</td>
<td>85.21</td>
<td>-1.82</td>
</tr>
<tr>
<td>LE Slat</td>
<td>87.06</td>
<td>87.02</td>
<td>-0.04</td>
</tr>
<tr>
<td>TE Flap</td>
<td>85.54</td>
<td>85.33</td>
<td>-0.21</td>
</tr>
<tr>
<td>Nose Landing Gear</td>
<td>76.76</td>
<td>76.76</td>
<td>0.00</td>
</tr>
<tr>
<td>Wing TE</td>
<td>74.31</td>
<td>74.41</td>
<td>0.09</td>
</tr>
<tr>
<td>Strut</td>
<td>-</td>
<td>67.16</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>91.89</strong></td>
<td><strong>91.27</strong></td>
<td><strong>-0.63</strong></td>
</tr>
</tbody>
</table>

- Main landing gear
  - Cantilever with 6 wheels; SBW with 4 wheels and \(\frac{1}{2}\) the strut length
- Wing strut modeled as wing TE noise
Conclusions

- A methodology for designing low-airframe-noise aircraft has been developed and implemented in an MDO framework.
- Reducing airframe noise by reducing approach speed alone, will not provide significant noise reduction without a large weight penalty.
- Therefore, more dramatic changes to the aircraft design are needed to achieve a significant airframe noise reduction.
- Cantilever wing aircraft can be designed with minimal TE flaps without significant penalty in weight and performance.
- If slat noise and landing gear noise sources were reduced (this is being pursued), the elimination of the flap will be very significant.
- Clean wing noise is the next ‘noise barrier’.
- SBW aircraft could have a similar or potentially lower total airframe noise compared to cantilever wing aircraft.
Future Work

◆ Important topics
  – Effects of reduced runway length
  – Effects on other noise sources
    • Increased drag at approach => Increased engine noise for same speed

◆ SBW’s and BWB’s should be considered in future studies
  – Clean wing noise model by Hosder et al.