A Methodology for Integrated Conceptual Design of Aircraft Configuration and Operation to Reduce Environmental Impact

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Motivation

- Over the last 35 years
  - Six-fold growth in air-travel capacity
  - Reduction in people impacted by aviation noise
  - 60% improvement in aircraft fuel efficiency
  - Reductions due to improved technology
- Pace has slowed
  - Often trading impacts
  - Need new ways to reduce environmental impacts
- Study interaction of aircraft and operation

Source: GAO’s survey of the nation’s 50 busiest commercial service airports.
Challenges

• Need to include aircraft operations into early stages of design.
  – Best aircraft will integrate benefits from both configuration and operation.

• Developing configurations and operations simultaneously yields a large design space.

• Require appropriate fidelity such that design space exploration is tractable and meaningful.
  – Generally (not always) a trade between result quality and run-time.
Achievements

• Developed a low-speed aerodynamic tool suitable for integrated design of operating procedure and aircraft configuration.
  - Accuracy similar to industry conceptual design tools
  - Tractable computational complexity and parameter space

• Integrated aircraft performance tools to evaluate operational procedures.

• Used optimization to explore a design space of current aircraft fleet operations.

• Performed a sensitivity study to demonstrate that both configuration and operational procedures can be studied simultaneously.
Configuration and Operation Integration

- **Pilot Inputs**
  - Control System (Fancy Auto-Pilot)
  - Engine Cycle (JT9D Interpolation)
  - Airplane Physical Model (dv/dt=−)

- **Configuration Inputs**
  - Low-Speed Aero (Flap Settings → Performance)
  - Noise-Power-Distance (Flap Settings → Noise Signature)
  - Integrated Noise Model

- **Outputs**
  - Trajectory
  - Cost Model
  - Time to Climb
  - Fuel Burn
  - Cost
  - Noise
Aerodynamic Model Fidelity

- Estimates drag polars for clean configurations to within ~1%
- High-lift drag polars to within ~10%
- Maximum lift coefficient and lift curve to within ~10%
- Calibration:
  - Boeing flight & wind tunnel tests
  - NASA wind tunnel tests
  - Empirical Lockheed method
Operational Design Space

- **Objectives**
  - Time to Climb, Fuel Burn, Noise, Operating Cost

- **Parameters**
  - Flap setting
  - Throttle setting
  - Velocity
  - Transition Altitude
  - Climb gradient*
  - **18 Total**

- **Constraints:**
  - Regulations
    - No pilot input below 684 ft
    - Initial climb at $V_2 + 15$ kts
  - Flap settings
  - Velocity
    - Min: stall
    - Max: max q
  - Throttle
    - Min: engine idle or positive rate of climb
    - Max: full power

*Note: Climb gradient is a parameter in the operational design space.
Design Space Exploration Methods

- Exploration Challenges
  - Islands of feasibility
  - Many local minima
  - Mixed discrete/continuous variables
  - Many design variable scales ($10^{-1} \rightarrow 10^4$)
  - Long function evaluation time (~2 minutes with noise)

- Sequential Quadratic Programming [Climb time: 312 s]
  - Stuck at local minima
  - Can’t handle discrete integers

- Direct Search (Nelder-Mead) [Climb time: 319 s]
  - Similar problems as SQP, but worse results

- Particle Swarming Optimization [Climb time: 319 s]
  - Slow running (8-12 hours), optimum not as good as Genetic Algorithm

- Genetic Algorithm [Climb time: 308 s]
  - No issues with any of the challenges of this problem.
  - No convergence guarantee and SLOW! Run-time ~24 hours.
  - But, best result.
Results (725,000 lbm)

All metrics have improved:

<table>
<thead>
<tr>
<th></th>
<th>Time</th>
<th>Fuel Burn</th>
<th>Noise (55 EPNdB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>485.5 s</td>
<td>6,817 lbm</td>
<td>477.6 mi²</td>
</tr>
<tr>
<td>Minimum Time to Climb</td>
<td>307.5 s</td>
<td>5,080 lbm</td>
<td>354.2 mi²</td>
</tr>
<tr>
<td>Minimum Fuel Burn</td>
<td>315.6 s</td>
<td>5,125 lbm</td>
<td>357.6 mi²</td>
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<tr>
<td>Minimum Noise</td>
<td>318.7 s</td>
<td>5,138 lbm</td>
<td>357.4 mi²</td>
</tr>
</tbody>
</table>
Takeoff Noise Sensitivity Studies

- Ex. Boeing 777-200ER
- Sensitivity study not Optimization
- Takeoff Certification Procedure
  - Full-power until at least 984ft, then cutback
- Simple operational procedure
  - 2 design variables
- Aircraft configuration
  - 60 design variables
  - 16 dominant variables studied
- Sensitivity of noise to each configuration parameter requires an optimization loop for cutback altitude
  - Configuration and operation are coupled

Baseline Certification Noise v Cutback Altitude

Effective Perceived Noise Level (EPNdB)

- Estimated Flyover
- Estimated Sideline
- AC36-1H Takeoff
- AC36-1H Sideline

Cutback Altitude (ft)
Takeoff Noise Sensitivity

- % change in minimum Sideline+Flyover
- All sensitivities are small.
Approach Configuration Analysis

- Ex. Boeing 777-200ER
- Two operational parameters
  - Glide slope
  - Velocity ($kV_s$)
- 17/60 aircraft configuration parameters studied
- Design Space Exploration:
  - Sensitivity study to determine effect of 10% change in each parameter
    - 19 parameters, 57 runs
  - Full-factorial study of dominant parameters
    - 4 parameters, 81 runs
• Considerably more sensitive than takeoff.
• Best combination: 10% faster and steeper, 1.12%
Conclusion

• An integrated analysis of aircraft configuration and operation shows significant opportunities to reduce environmental impact.

  – Found an optimized departure procedure for the 747-200 that simultaneously reduced:
    • 178 seconds in time to climb. (37%)
    • 1,700 lbm in fuel consumption. (26%)
    • 123 square mile reduction in 55 EPNdB noise exposure area. (26%)
    • $1,800 in operating costs\(^1\) (2.6%)

  – Demonstrated coupling between configuration and operation and that certification noise is sensitive to both.

• This highlights the benefit of multidisciplinary optimization and examining both configuration and operation at the early stages of design.

\(^1\)2007 dollars
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Questions?