Gradient-Based Propeller Optimization with Acoustic Constraints

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Urban Air Mobility Represents a New Challenge for Aircraft Acoustics
What We’d Like To Do

Develop toolchain for large-scale optimization of a tilt wing turboelectric UAM concept from Johnson et al.[1], with coupled structural, aerodynamics, acoustics, propulsion, thermal, and trajectory disciplines.
What We’ve Done Here: Propeller Optimization With Fixed Relative Observer (Essentially Wind Tunnel Configuration)
Mid-Fidelity Models, Gradient-Based Optimization Enable Large-Scale Analysis

- **Mid-fidelity aerodynamic models:**
  - Blade element momentum theory (BEMT): Gur and Rosen[2, 3], Wisniewski et al.[4].
  - Vortex lattice: Miller and Sullivan[5].

- **High-fidelity aerodynamic models:**
  - Computational Fluid Dynamics: Pagano et al.[6, 7].

- Most examples use some form of the Ffowcs-Williams Hawking (FWH) approach[8] for the acoustic model.

**Methods for this work**

BEMT and FWH, all with analytic derivatives. Focusing on developing tool chain.
BEMT Limitations

- No interaction between blade elements, so spanwise flow not captured (so no blade sweep).
- Here, used steady, level flight, so predicted loads will be steady (not changing with propeller rotation).
- OK for steady, forward flight. Probably not adequate for VTOL.
BEMT Implementation: OpenBEMT

- Initially developed by Hwang and Ning[9] to study the X-57 Maxwell concept.
- Uses OpenMDAO framework[10] to propagate outputs and their derivatives through each stage of the calculation for gradient-based optimization.
Uses distributed flow properties on surface (e.g., propeller blade surface) to calculate source term strengths, and then the acoustic pressure time history at a specified location (“acoustic observer”).

Needed inputs directly correspond to BEMT outputs, and about the same computational expense as BEMT.

Limitations & Assumptions
- Steady loading configuration captures only steady acoustic sources.
- Elongated surface in lifting line direction.
- Assumes acoustic observer distance much larger than blade thickness.
FWH Implementation: ANOPP2

- Compact F1A calculation is implemented in NASA Langley’s second generation Aircraft Noise Prediction Program[14] (ANOPP2).
- ANOPP2 is a comprehensive noise prediction framework, much more than just F1A.
- The Compact F1A implementation has been differentiated for use with gradient-based optimization, and is used in this work.
XDSM Diagram: Optimization Overview

- $D_{\text{hub}}$: hub diameter
- $\tilde{v}_\infty$: free-stream velocity
- $c_i$: chord
- $Y_i$: blade element location
- $T$: thrust
- $D_{\text{prop}}$: propeller diameter
- $\tilde{x}$: observer location
- $\theta_i$: twist
- $\tilde{f}_i$: blade element loading
- $\eta$: efficiency

Symbols:
- $c_i^\ast$, $\theta_i^\ast$, $D_{\text{prop}}^\ast$, $\omega^\ast$
- $c_i$, $\theta_i$, $D_{\text{prop}}$, $\omega$
- $\eta^\ast$, $T^\ast$
- $\eta$, $T$
- $\tilde{Y}_i$, $\tilde{f}_i$
- $\tilde{X}$, $\tilde{v}_\infty$
- $\text{OASPL}$, $\text{OASPL}^\ast$
XDSM Diagram: ANOPP2 Detail

Blade Geometry

\( \omega, Y_i, c_i \)

\( \omega, Y_i, \vec{f}_i \)

\( \omega, \vec{x}, \vec{v}_\infty \)

\( \vec{y}_i, \Lambda_i \)

\( \vec{F}_i \)

Blade Loads

Compact F1A

\( p_m, p_d \)

Narrowband Spectrum

\( \langle p^2 \rangle \)

OASPL

OASPL
Test Case: X-57 Cruise Propeller Properties

Test case parameters were taken from the NASA’s X-57 Maxwell[15] cruise propellers:
Test Case: X-57 Cruise Propeller Properties

Test case parameters were taken from the NASA’s X-57 Maxwell[15] cruise propellers:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tbody>
<tr>
<td>Altitude</td>
<td>10 m</td>
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<td>Cruise speed</td>
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<td>Diameter</td>
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<td>Hub diameter</td>
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<td>Blade count</td>
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Two Optimization Cases

Multi-objective optimization: **maximize propeller efficiency** for **constant thrust**, with **OASPL constraint** systematically reduced to form a Pareto frontier.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
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<td>maximize efficiency</td>
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<tr>
<td>with respect to twist</td>
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<td>with respect to <strong>diameter</strong>(^1)</td>
<td>75 cm</td>
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<td>with respect to <strong>RPM</strong></td>
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<td>None</td>
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<td>subject to total thrust = 700. N</td>
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<tr>
<td>sideline OASPL</td>
<td>x (\Delta dB)</td>
<td>x (\Delta dB)</td>
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\(^1\) Optimizer chose upper bound for each run.
Optimizations are Pretty Quick

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SNOPTC EXIT 0 -- finished successfully
SNOPTC INFO 1 -- optimality conditions satisfied

Time for MPS input: 0.00 seconds
Time for solving problem: 9.54 seconds
Time for solution output: 0.00 seconds
Time for constraint functions: 9.54 seconds
Time for objective function: 0.00 seconds

1
Significant Difference Between the Two Pareto Frontiers

![Graph showing the comparison between two cases for propeller efficiency and delta OASPL, dB. The graph indicates a significant difference between the two cases, with Case 2 showing a higher efficiency compared to Case 1.]
Slower Propellers Are Quiet Propellers

![Graph showing propeller rotation rate vs. delta OASPL dB. The graph compares Case 1 and Case 2. Case 1 has a lower curve, indicating quieter performance.]
Case 1 Strategy: Shift Chord Inboard to Quiet Propeller

The graph shows the acoustic pressure level (OASPL) in dB at different radial locations (m) and chord lengths (cm) for a propeller. The legend indicates the unconstrained OASPL, with values ranging from 0.0 dB to -1.2 dB. The radial location is marked from 0.2 m to 0.7 m, and the chord length from 2 cm to 14 cm. The graph highlights the differences in OASPL between the hub and tip of the propeller.
Case 2 Strategy: Increase Chord to Maintain Thrust

![Graph showing the relationship between radial location and OASPL for different chord lengths, with unconstrained OASPL marked with a dashed line.](image-url)
Case 1 Strategy: Shift Twist Inboard to Quiet Propeller

![Graph showing OASPL and twist distribution](image-url)
Case 2 Strategy: Increase Twist to Maintain Thrust

Decreased RPM + increased pitch reminiscent of Berton & Nark[16]
Case 1: Move Axial Loading Inboard
Case 2: Maintain Axial Loading

[Graph showing axial load vs radial location with unconstrained OASPL indicated]
Case 1: Chord and Twist Impact Circumferential Loading

OASPL, ΔdB

Circumferential Load, N

radial location, m

hub
tip

unconstrained OASPL

NASCAR

25
Case 2: More Chord and Twist Increase Circum. Loading

![Graph showing circumferential load and OASPL (Objective Averaged Sound Pressure Level)]

- **Legend:**
  - **Unconstrained OASPL** (red dashed line)
  - **Other curves** (various lines)

- **Axes:**
  - **Circumferential Load, N** vs. **radial location, m**
  - **OASPL, ΔdB**

- **Key Points:**
  - **Hub** and **Tip** locations are marked.

- **Data Points:**
  - Various radial and circumferential loads are displayed, with corresponding OASPL values.

- **Color Coding:**
  - Different colors represent different radial locations.

- **Scale:**
  - OASPL values range from 0 dB to 45 dB.
  - Radial location ranges from 0.2 m to 0.7 m.

- **NASA Logo:**
  - Present on the page.
Propeller aerodynamics and acoustics codes were combined within an MDAO framework and exercised on two test cases.

Near-term next steps:
- fixed-observer case with trajectory optimization
  - Goal is to extend Berton & Nark’s[16] recent idea of reducing the noise of a hypothetical propeller-driven electrified GA aircraft through pitch control.
- Replace BEMT with higher-fidelity approach

Ultimate goal: include this tool chain in a larger UAM optimization (trajectory, power generation, vehicle weight).


References II


References III


References V


Compact F1A


- **Compact F1A**: integration surface is replaced with spanwise lifting line.

\[
p(t) = \frac{1}{4\pi} \int \left[ \rho_\infty \Lambda C_{1A} + \frac{1}{c_\infty} \left( \dot{F}_i D_{1A,i} + F_i E_{1A,i} \right) \right]_{\text{ret}} dl
\]

\[C_{1A}, D_{1A}, E_{1A}\] are function of blade motion only, **large in regions where blade motion is high**.