Design of a Low-Noise Propeller with Low-Order Tools

Preliminary Results

Daniel Ingraham
NASA Glenn Research Center
daniel.j.ingraham@nasa.gov

NASA Acoustics Technical Working Group
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Motivation

- We want to do large-scale optimizations of urban/advanced air mobility vehicles, with acoustics.
  - Noise anticipated to be a limiting factor for UAM/AAM concepts.
- Need gradient-based optimization techniques to navigate the design space efficiently.
- First step: Can we do this for propeller noise?

Goal

Design an efficient, low-noise propeller using gradient-based optimization and low-fidelity tools, and test in NASA LaRC's Low Speed Acoustic Wind Tunnel facility (LSAWT).

How?

- Models:
  - aerodynamics: blade element momentum theory (BEMT)
  - acoustics: compact form of Farassat's formulation 1A
- Optimization framework
  - OpenMDAO (NASA Glenn)
  - SNOPT (Stanford), via pyOptSparse (U. of Michigan MDO Lab)

Propeller Aerodynamic model using CCBlade.jl

- Blade Element Momentum Theory code from Andrew Ning, BYU
  - Efficient
  - Incorporates blade geometry into calculation
- Two C's:
  - Continuous (required for gradient-based optimization)
  - Convergent (helpful for large-scale optimizations)

Propeller Acoustic model using Compact F1A

- Thickness and loading noise prediction from compact form of Farassat's "Formulation 1A," including Len Lopes (NASA LaRC) compact monopole approach.
  - Compact == reduces surface integrals associated with traditional acoustic analogies to line integrals.
- Assumes surface is elongated in the "line" direction (like a propeller blade)
- Tonal acoustics only
- Advantages
  - fast
  - inputs line up with BEMT outputs

OpenMDAO: gradient-based optimization made "easy"

- Python framework
- User defines `Components`, units of computation with inputs and outputs, optionally organized into arbitrarily-nested `Groups`.
- OpenMDAO manages data passed from one `Component` to another, assembles Jacobian, calls optimizer with necessary arguments, etc..

Results will be compared to a baseline design

Baseline design from Nik Zawodny (NASA LaRC).

- 24 inch diameter
- 3 blades
- Constant 1.5 inch chord
- Helical twist distribution
- NACA 0012 airfoil sections throughout
- Intended RPM ≈ 7110

Has been tested in LSAWT. Aerodynamic and acoustic data available.

Problem Setup

- Objective: maximize cruise efficiency
- Design variables:
  - Chord and twist along the blade
  - Propeller RPM at each operating point (maybe)
- Constraints:
  - thrust at each operating point equal to baseline design's value
  - sideline OASPL constraint at *one operating point* (sweeping)
    - Baseline prediction for hover: 101 dB
    - Baseline prediction for cruise: 98 dB

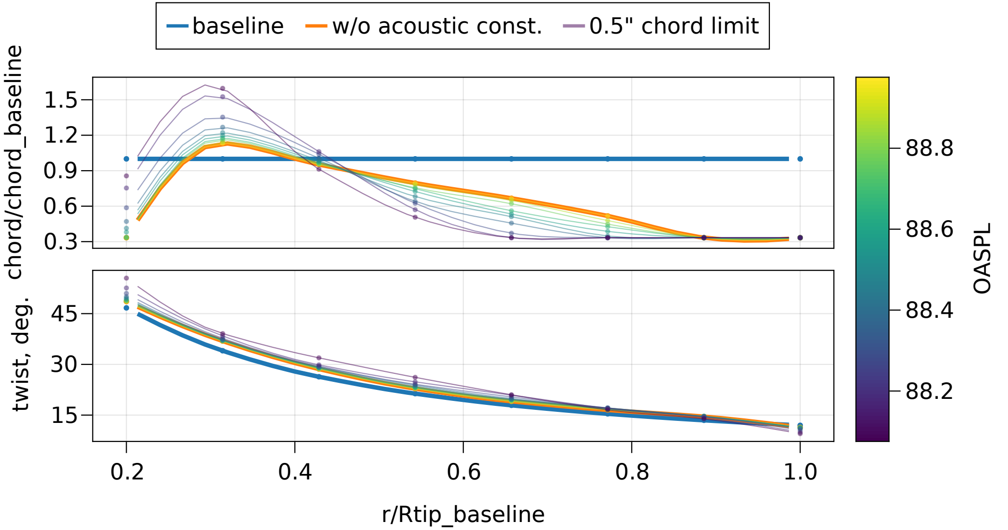
Both single-point and two-point optimizations considered

Will show results of optimizations considering

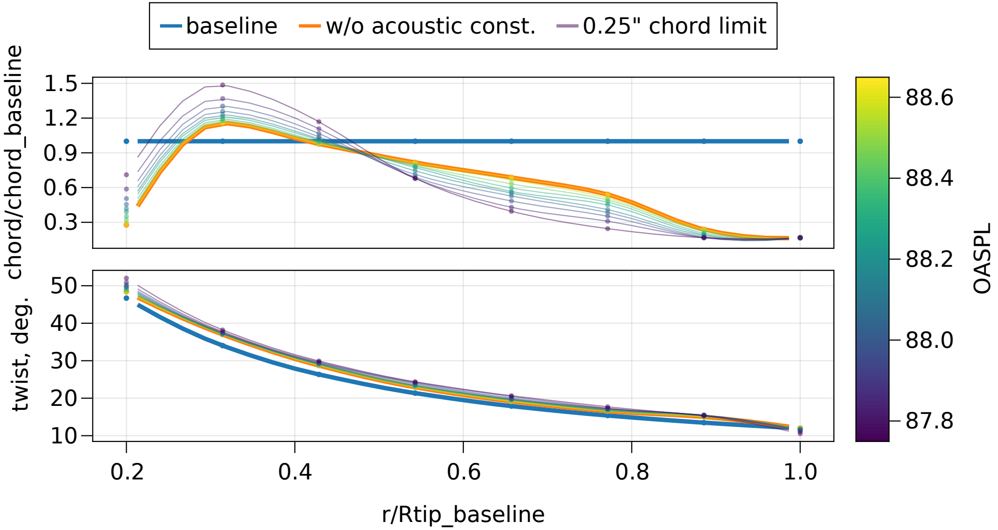
- cruise operating point only
  - with and without RPM design variable
- takeoff operating point only
  - with and without RPM design variable
- takeoff+cruise
  - RPM design variable at both operating points (like a fixed-pitch, RPM-controlled propeller/rotor)

Results

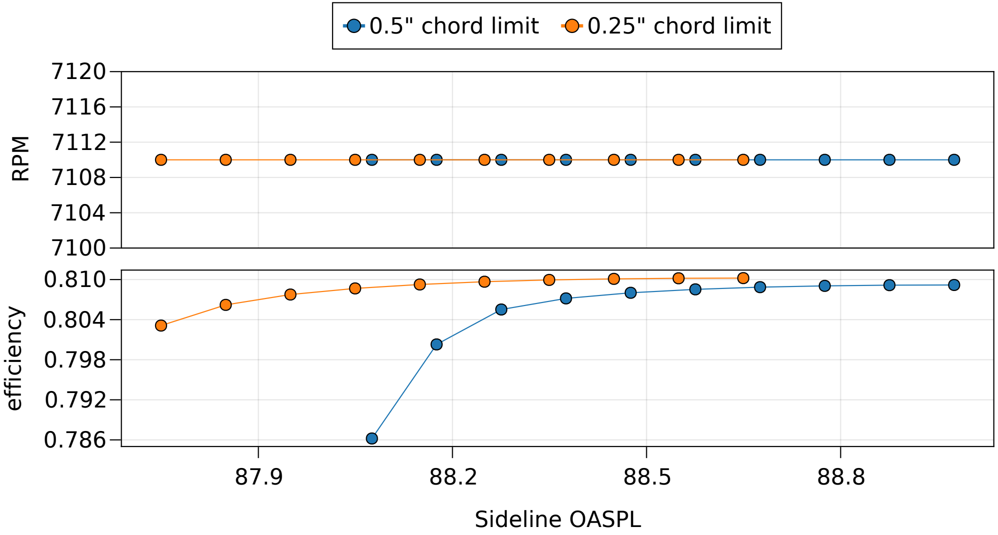
Cruise-only optimization w/ fixed RPM yields very thin blade



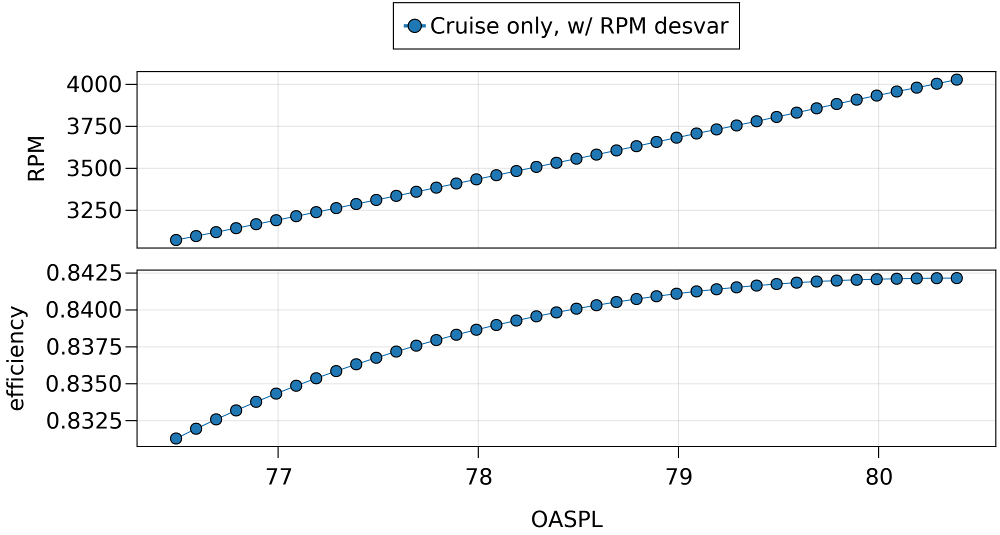
Cruise-only optimization w/ fixed RPM yields very thin blade



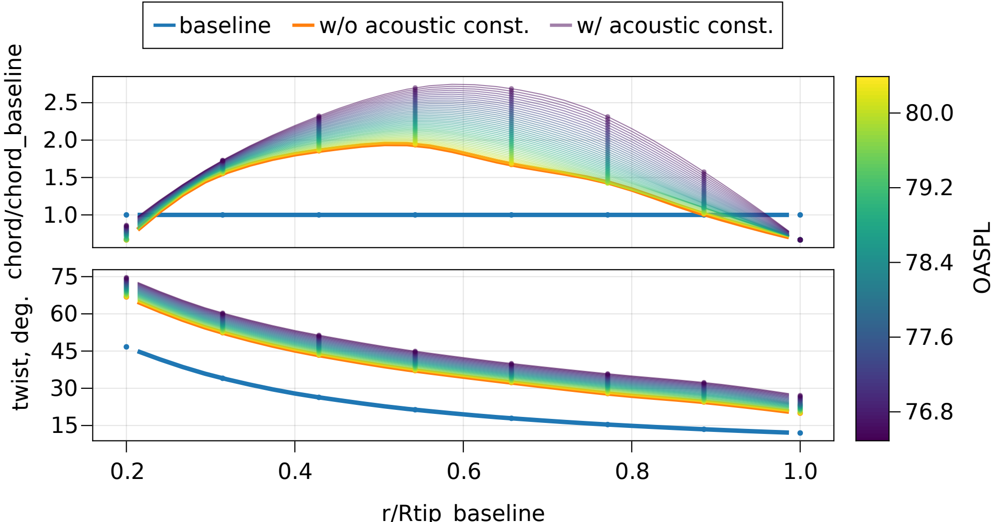
Thin blades are nice for aero & acoustics, pose structural challenges



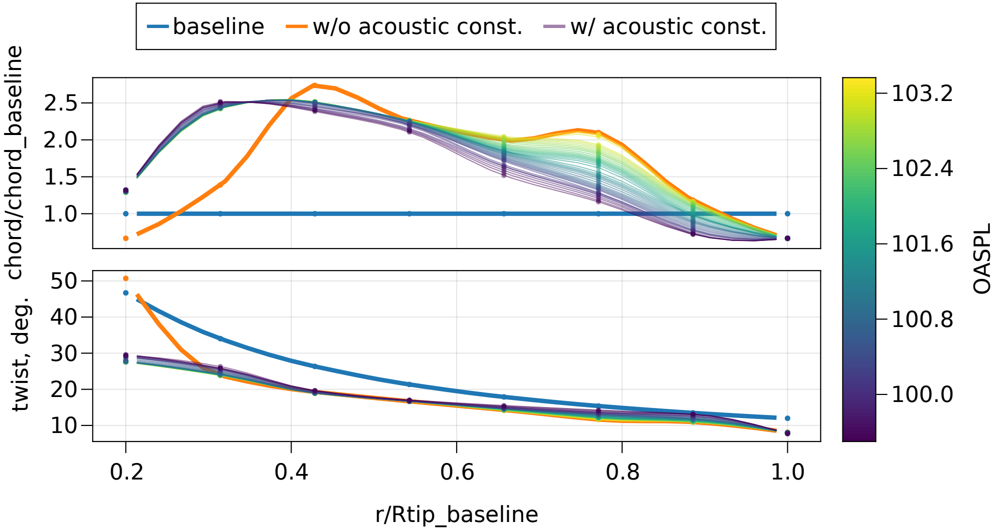
Cruise-only optimization w/ RPM design var: slow blades are quieter



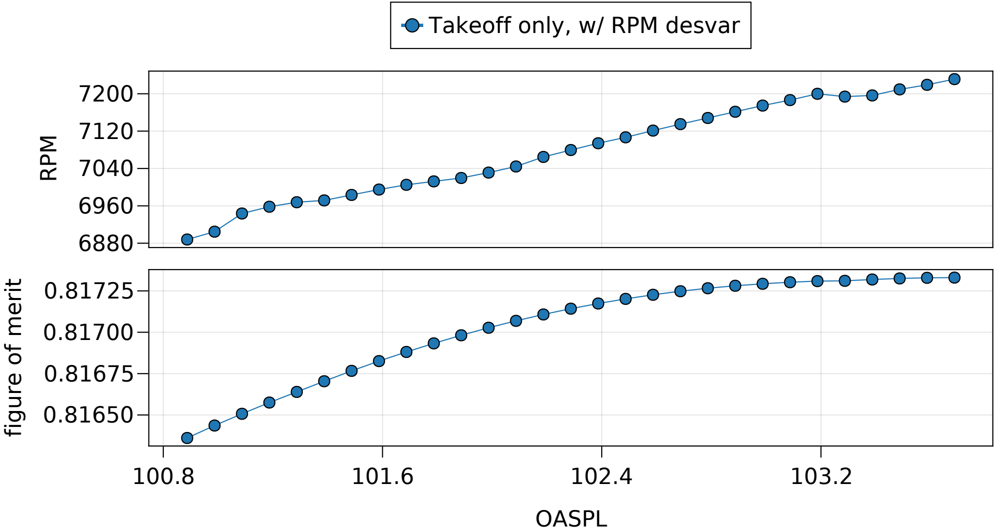
Cruise-only optimization w/ RPM design var: thicken blade to meet thrust constraints



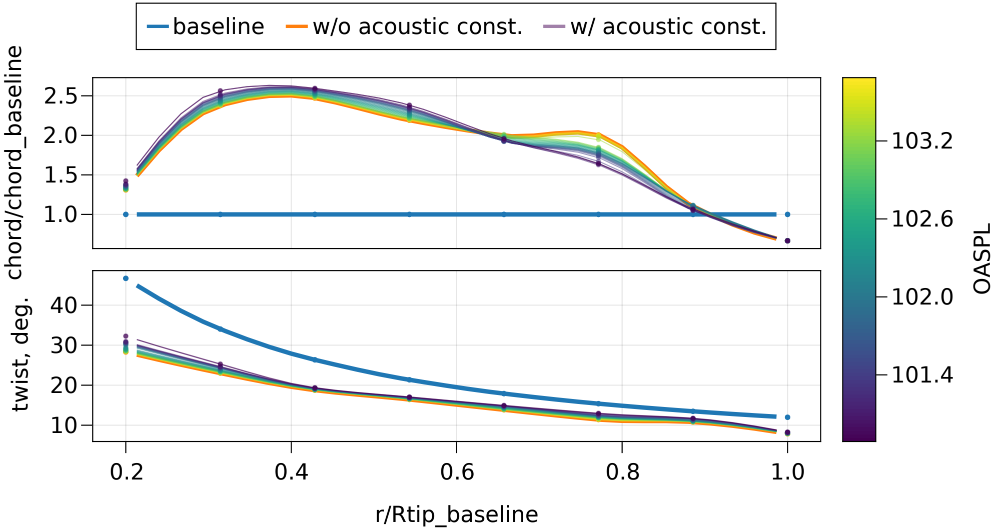
Takeoff-only optimization w/ fixed RPM: less chord, more twist $\frac{1}{3}$ from tip



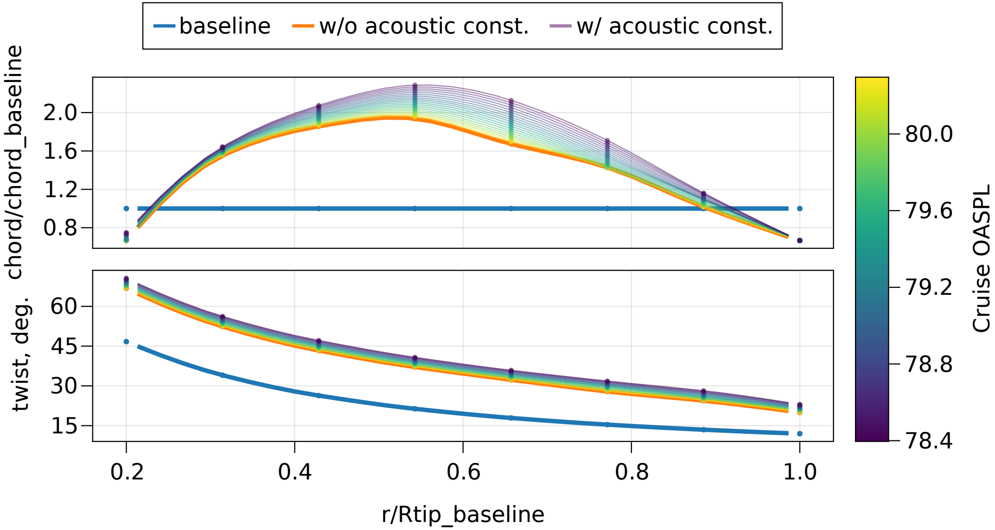
Takeoff-only optimization w/ RPM design var: slower is quieter, again



Takeoff-only optimization w/ RPM design var: shift chord inboard



Takeoff and cruise, sideline cruise acoustic constraint



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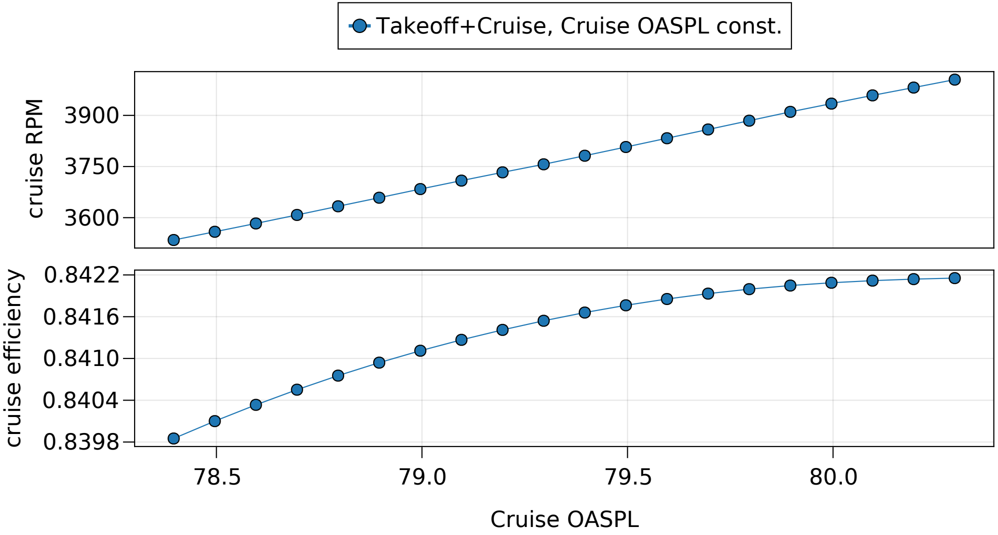
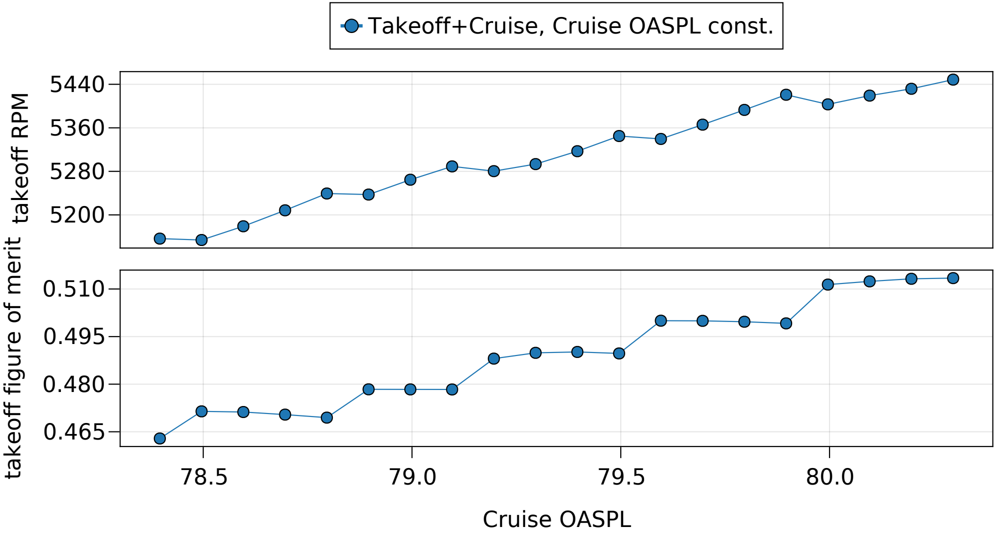


Takeoff and cruise, sideline cruise acoustic constraint



Next Steps

- Improve takeoff performance for the two-point optimizations
- Increase complexity of acoustic metric
  - A-weighting
  - both operating points
  - > 1 observer location
- Add propeller diameter to design variables
- Add broadband noise model
- Longer term plans:
  - Increase fidelity of propeller aerodynamic model
  - Incorporate this toolchain into larger UAM optimization, including power generation, vehicle aero, trajectory, thermal managment, etc..

Thanks!

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