

Blade and Trajectory Optimization of a Propeller-Driven Electric Aircraft with Acoustic Constraints

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New Class of Urban Air Mobility Vehicles Will Need to be Quiet

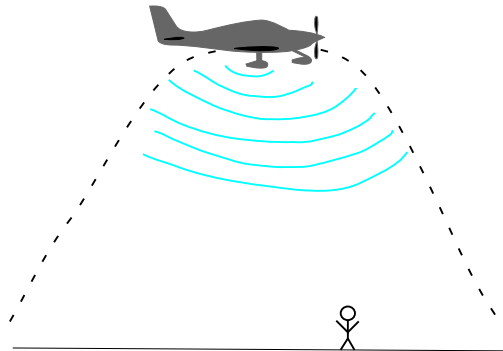
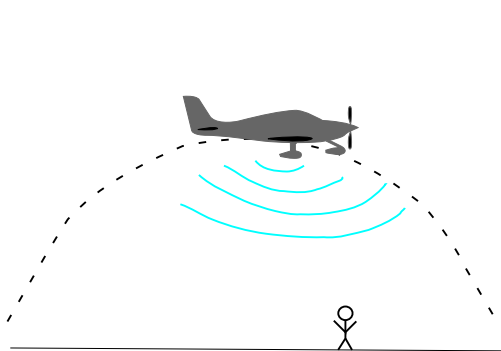


Two strategies noise control:

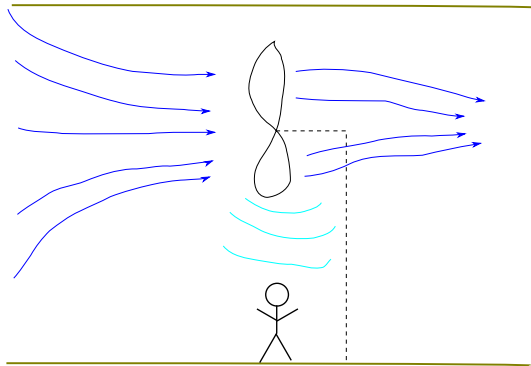
design a quieter aircraft

or

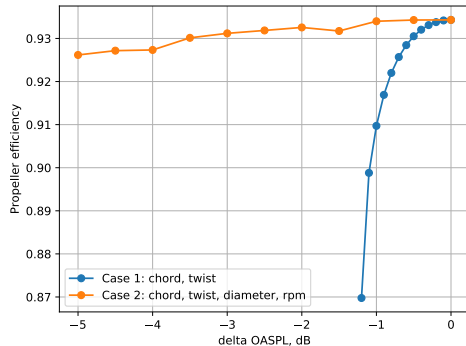
fly to minimize noise



Previous work: Vary twist, chord, diameter and RPM
to design a quieter propeller with a fixed relative observer

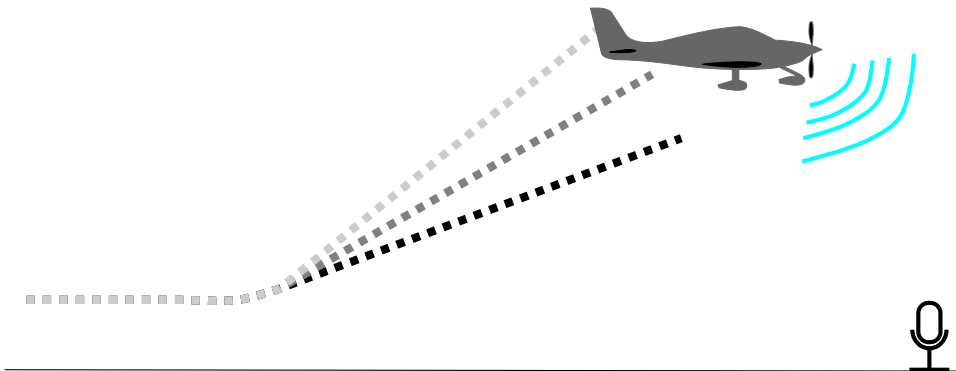


A fixed relative observer mimics a wind
tunnel configuration

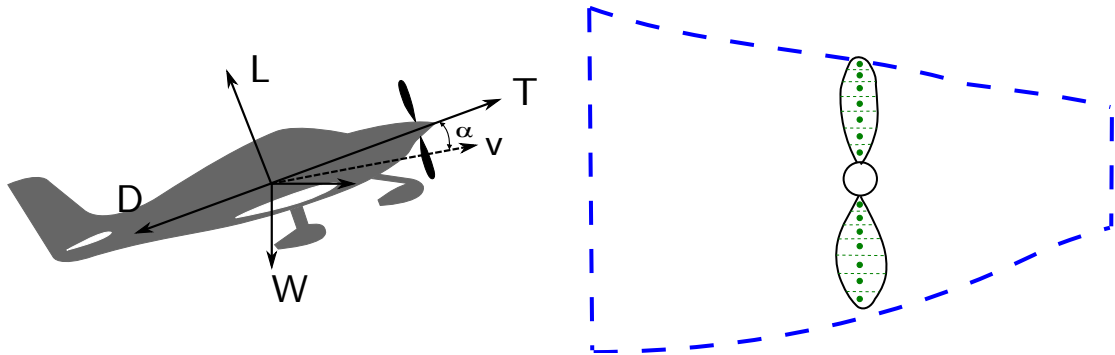


Our current goal: Minimize the noise at a ground observer, by simultaneously optimizing the physical design and the takeoff trajectory

- Berton & Nark[5] showed a GA aircraft could be made 4 dB quieter by changing the propeller RPM and pitch (after replacing the piston engine with a hypothetical electric motor)



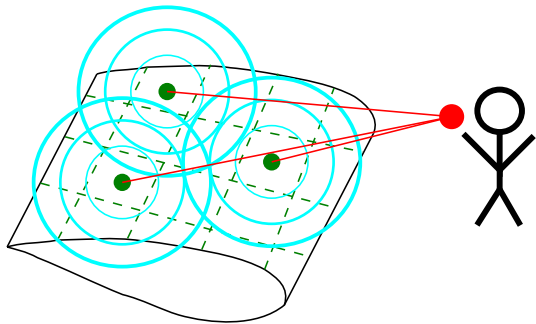
We modeled the trajectory with 2D equations of motion
and modeled the propeller with BEMT



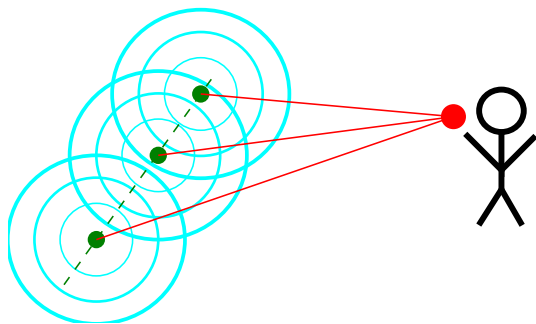
- ▶ Using CCBlade.jl Blade Element Momentum Theory (BEMT) implementation from Ning[1].
- ▶ Vehicle aerodynamics taken from the aforementioned Berton & Nark study.

Acoustics are modeled with a compact form of the Ffowcs Williams-Hawkings acoustic analogy

Full F1A[3, 4]

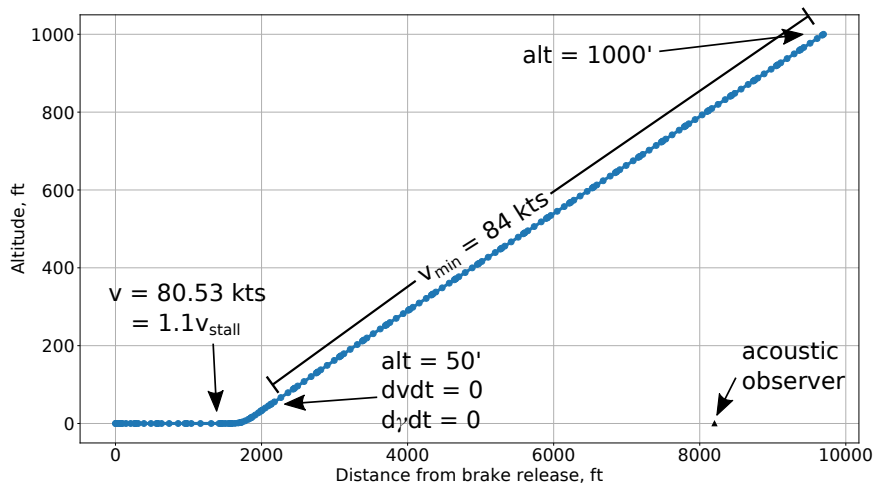


compact F1A, L. Lopes[2]



- ▶ 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").
- ▶ Here, only looking at tonal propeller noise.

Problem formulation: Vary prop design & RPM to minimize energy used, subject to a constraint on noise level at the ground observer.

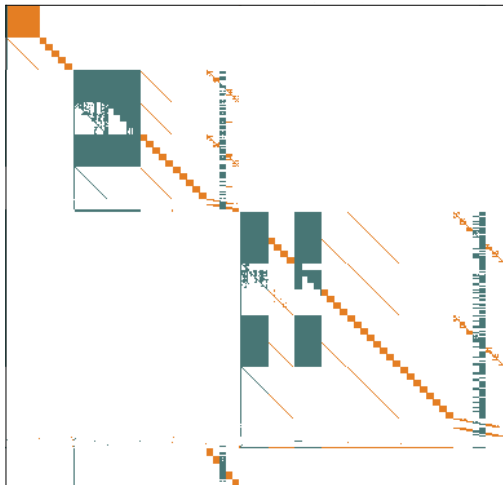


The optimization has 498 design variables and 494 constraints

	Description	Quantity
minimize	Total propulsive energy = shaft power · trajectory duration	
with respect to	Propeller RPM	1
	Propeller chord	6
	Propeller twist	6
	Range	112
	Altitude	87
	Airspeed	112
	Flight path angle	87
	Angle of attack	87
subject to	Final takeoff_roll airspeed	1
	Final takeoff altitude	1
	Final takeoff flight path angle time derivative	1
	Final takeoff airspeed time derivative	1
	Final climb altitude	1
	Target OASPL	61
	Pseudo-spectral constraints	428



The Jacobian is sparse, so coloring reduces cost of computing derivatives.
58 forward Solves and 35 reverse solves (75.1% reduction)



reverse mode

forward mode

We assembled the optimization using OpenMDAO, Dymos, and SNOPT



<https://openmdao.org/>

dymos

<https://openmdao.github.io/dymos/>

SNOPT

[https:](https://web.stanford.edu/group/SOL/snopt.htm)

[//web.stanford.edu/group/SOL/snopt.htm](https://web.stanford.edu/group/SOL/snopt.htm)



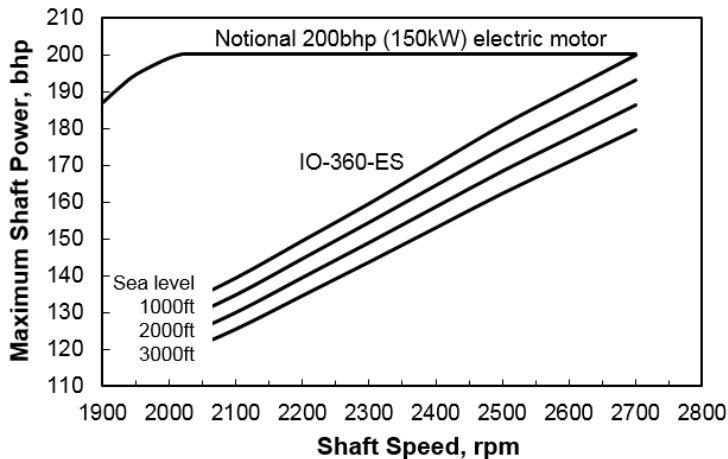
Is this a well-posed optimization problem?

We're not sure.

It is definitely not working yet...

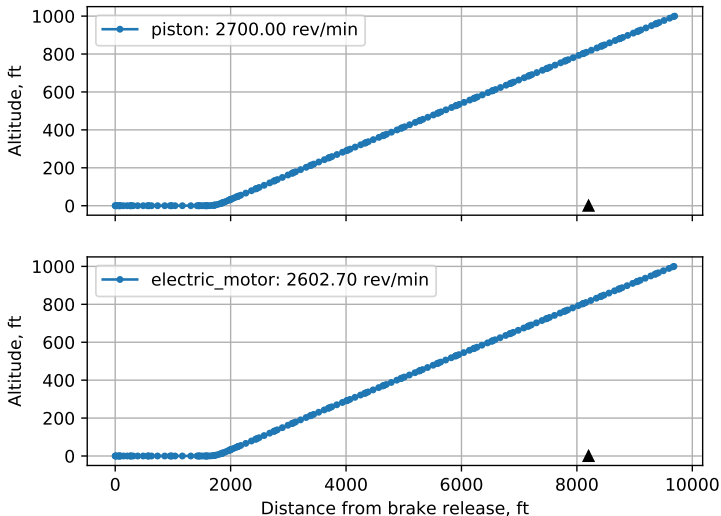


Examined both traditional and electric propulsion cases,
with and without acoustic constraints

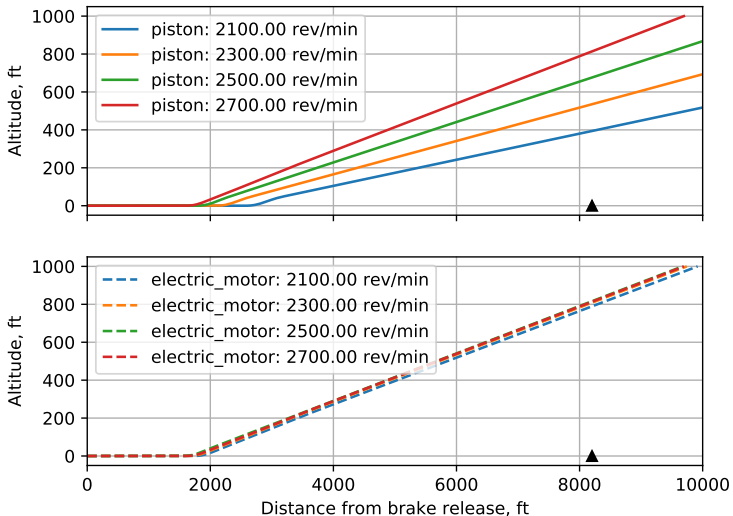


- Engine/motor power curve from Berton & Nark[5].

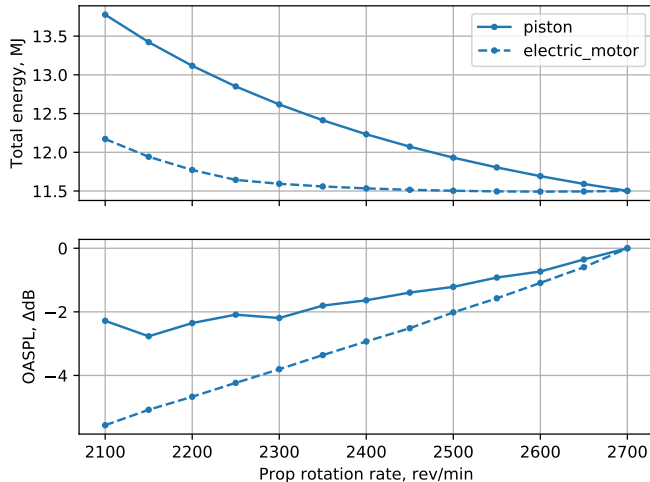
Without an acoustic constraint, no problem finding an optimal trajectory



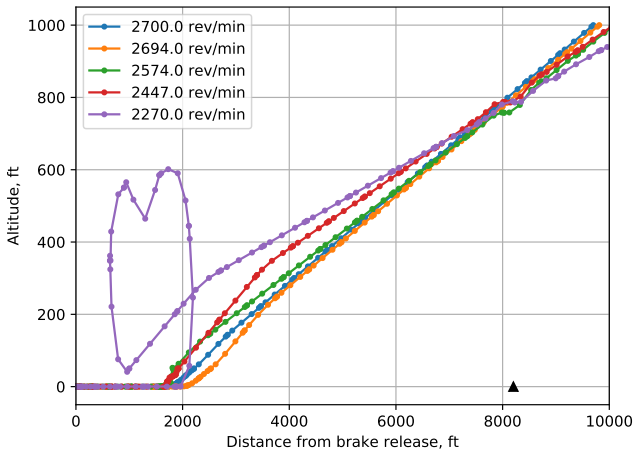
We removed RPM from the design variables, ran a sweep of optimizations



The manual RPM sweep shows a smooth trade between noise and energy, indicating that this is a well posed optimization problem



But the optimization with an RPM design variable and an acoustic constraint has problems
(unless loop-de-loops are allowed, then we're good)



Perhaps the problem is in the derivatives for the acoustic constraint?

Derivative of Mean Squared Pressure w.r.t. propeller rotation rate

Algorithmic Differentiation : 2.429575e-03

Complex-step : 2.429575e-03

Absolute Error: 5.288698e-18

Derivative of Mean Squared Pressure w.r.t propeller blade location

Algorithmic Differentiation : 5.411979e-04

Complex-step : 5.411979e-04

Absolute Error: 3.151406e-17



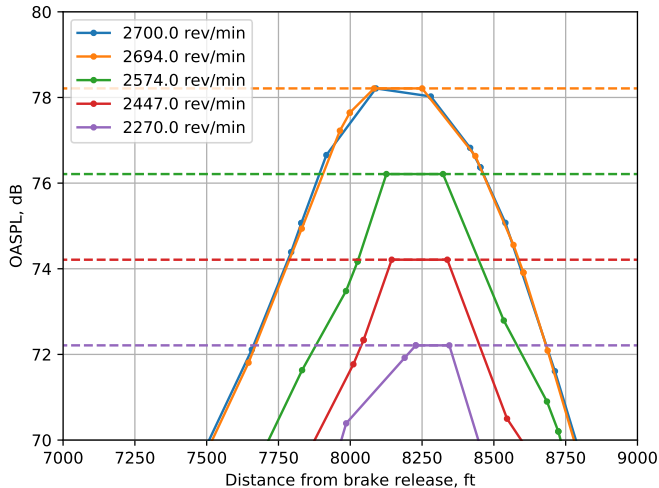
What about the scaling?

```
1 notes.rst 2 local0 3 local1 4 local2 5 slides.tex 6 problem.py 7 rpm.py 8 plot rpm.energy.oaspl.py 9 plot trajectory for paper.py 10 plot time.oaspl.py 11 plot.oaspl.py
(r20) disgraphGSLR10000228 piston % zathura time.oaspl.pdf
(r20) disgraphGSLR10000228 20_29_noise_constraint % ls
00 first try
01 adjust takeoff_refs
02 adjust takeoff_refs_again
03 adjust takeoff_refs_again
04 adjust.oaspl_ref
05 adjust.oaspl_ref_again
06 adjust_rpm_ref
07 adjust_rpm_ic
08 more adjust_rpm_ref
09 adjust_climb_refs
10 adjust_climb_refs
100 even_more_climb_grid
101 less_rpm_ref
102 ipopt try
103 even_less_rpm_ref
104 more.obj_ref
105 even_lower_rpm_ref
106 even_lower_rpm_ref
107 more.oaspl_ref
108 switch_rpm_ref
109 more_rpm_ref_adjustment
110 more_rpm_ref_adjustment
111 adjust_climb_refs
112 different_rpm_ic
113 more_acoustic_ref
114 more_climb_segments
115 increase_objective_ref
116 decrease_objective_ref
117 increase_objective_ref
118 ddt_gamma_path_constraint
119 less_rpm_ref
120 113_ref.adjustments
121 117 more_constraint_steps
122 119 more_ref.adjustments
123 11 adjust_rpm_ref
124 121 more_acoustic_ref
125 lower_gamma_ref
126 even_lower_gamma_ref
127 ddt_gamma_path_constraint
128 ddt_gamma_path_constraint
(r20) disgraphGSLR10000228 30_29_noise_constraint %
126 alpha.polynomial.control
127 alpha.polynomial.control_reset_scaling
128 127 lower_objective_ref
129 ddt_gamma_path_constraint_reset_scaling
130 high_objective_ref
131 130 less_climb_grid
132 adjust.obj_ref
133 131 even_less_grid
134 manual_rpm.pencil.more_rpm
135 manual_rpm.pencil.more_grid
136 reset_scaling_more_climb_grid
137 ddt_alpha_limit
138 171_ref.stop_size
139 170_ref.ref0
140 137 more_climb_grid
141 137 high_order.alpha.constraint
142 check_totals
143 139 more_climb_grid
144 14 15 rpm_ic
145 141 bigger_acoustic_ref
146 constant.pencil.threshold
147 constant.pencil.threshold_reset_scaling
148 constant.pencil.threshold_manual_rpm
149 144 with_check_totals
150 adjust_rpm_ref
151 147 more_adjust_rpm_ref
152 149 adjust something else
153 150 higher_acoustic_ref
154 151 lower_acoustic_ref
155 152 higher_acoustic_ref.tight_tol
156 153 148 more_adjust_rpm_ref
157 154 no 10
158 157 no 10
159 157 reset
160 157 uncolored_check_totals
161 154 144 even_more_climb_defect_refs
162 159 158 with_check_totals
163 15 more_rpm_ref
164 160 159 with_msp_banded_pencil
165 161 msp.pencil.vtf
166 157 with_time_refs
167 161 lower_acoustic_ref
168 163 manual_rpm
169 163 even_lower_acoustic_ref
170 higher_rpm_ref
171 lower_rpm_ref
172 even_lower_rpm_ref
173 more_steps
174 more_climb_refs
175 bigger_acoustic_ref
176 176 bigger_check_totals_step
177 171_ref.stop_size
178 174 even
179 174 reduce_with_incorrect_x_size
180 174 smaller_acoustic_ref
181 176 manual_rpm_renorm
182 178 tighter.oaspl.constraint
183 180 178 more_grid
184 181 178 smaller_rpm_ref
185 even_smaller_rpm_ref
186 183 even_smaller_rpm_ref
187 bigger_rpm_ref
188 185 slightly_lower_rpm_ref
189 even_slightly_lower_rpm_ref
190 187 bigger_acoustic_ref
191 rpm.pencil.one
192 objective_ref
193 184 reset_rpm_ref
194 186 no_coloring
195 191_ref.rpm
196 192 back_to.oaspl.constraint
197 constrain.uniform.oaspl
198 194 192 climb.alt_refs_for_takeoff
199 194 reset_rpm_ref
200 196 more.polynomial.control
201 no_alpha_rate_2_constraint
198 198 no_alpha.polynomial.control
199 more_acoustic_constraint
200 alpha.check
201 with_time_options
202 18 reset_refs
203 201.alpha.polynomial.control_everywhere
204 no_takeoff_climb_phase
205 202 more_grid
206 203 no polynomial.controls
207 204_alpha2_rate_limit
208 201 no_tas_lower_climb
209 takeoff_connected
210 rpm_ref
211 tas.takeoff_boundary.constraint
212 211 with_simulate
213 takeoff_tas_rate_limit
214 more_takeoff_tas_rate_limit
215 more_takeoff_grid
216 decrease_tas_ref_takeoff_phase
217 increase_acoustic_constraint_ref
218 decrease_acoustic_ref
219 lower_rpm_ref
220 rpm_ref
221 smaller_acoustic_ref
222 acoustic_ref_8
223 222 smaller_rpm_ref
224 224 narrow_rpm_range
225 224 more_rpm
226 complex_step
227 225 more.iterations
228 221 new.dot
229 221 reversediff
230 big.oaspl.constraint
231 big.oaspl.constraint.more.iterations
232 23 adjust_climb_tas_defect_ref
233 24 rpm_ref
26 ks_constraint
27 ks_constraint_try_2
28 ks_constraint_manual_rpm
29 20_renorm_more.iterations
30 more_rpm
31 rpm_and.oaspl_ref
32 more_grid
33 even_more_grid
34 31 butterworth_filter
35 34_shifted.butterworth_filter
36 36_rdot.constraint
37 36 ad_hoc.acoustics
38 37 no_coloring
39 35 select_indices
40 31.oaspl.constraint
41 39 rpm_ref
42 41.oaspl_ref_switching
43 41 defect_refs
44 huge.oaspl.constraint
45 adjust_defect_refs
46 msp
47 no_ks
48 adjust_defect_refs
49 bound_gamma_r
50 no_src_time
51 oaspl_indices
52 lower_obj_ref
53 back_to.oaspl
54 52 adjust_defect_refs
55 ad_hoc_msp_first_try
56 ad_hoc_msp_real_constraints
57 even_more_constraints
58 no_indices
59 56.updated.ad_hoc_msp
60 59 with_real_acoustics
61 60.oaspl
62 61.aggressive_constraint
63 rpm_ref
64 more_rpm_ref
65 takeoff_defect_refs
66 even_more.oaspl.constraint
67 reset_defect_refs
68 more_takeoff_grid
69 more_climb_grid
70 big_acoustic_ref
71 slightly_smaller_acoustic_ref
72 even_smaller_acoustic_ref
73 more_takeoff_grid
74 74_rdot.constraint
75 74 ad_hoc.acoustics
76 75 reset_defect_refs
77 gamma_rate_path_constraint
78 manual_rpm_new_model
79 78 rpm_ref
80 manual_rpm_ad_hoc_noise
81 manual_rpm_more_climb_grid
82 oaspl.mean.constraint
83 pseudo.epsl.constraint
84 83.constant_climb_gamma
85 manual_rpm_pseudo.epsl
86 85 more_grid
87 manual_rpm_pseudo.epsl_interp
88 pseudo.epsl.constraint_uniform.oaspl
89 88 less_climb_grid
90 combined_takeoff_climb_phase
91 91 obj_ref
92 more_obj_ref
93 more.oaspl.interp_points
94 94 more_climb_grid
95 rpm_ref
96 less_rpm_ref
97 less_climb_grid
98 less_rpm_ref
99 manual_rpm_pseudo.epsl_more_interp
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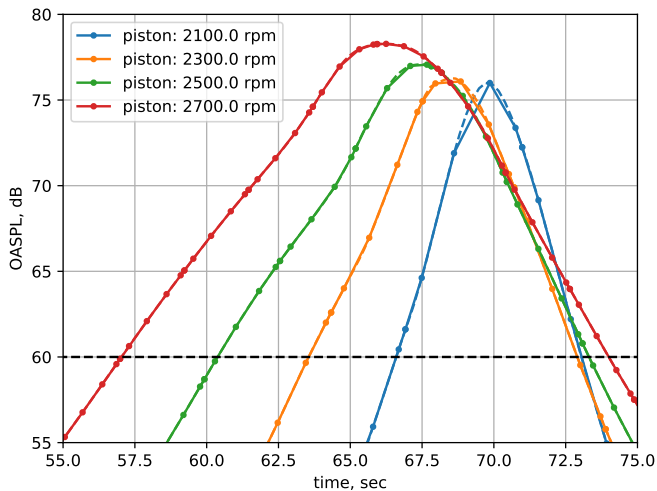
(Each directory contains an attempt at adjusting the scaling.)



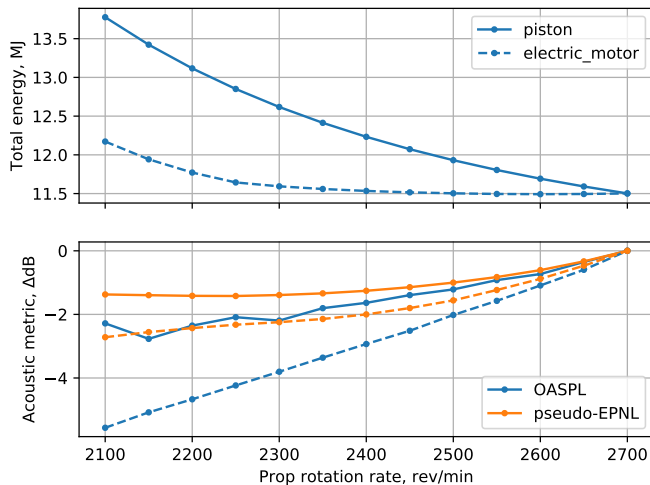
The optimizer manipulates the acoustic constraint by moving the discrete points where it is evaluated



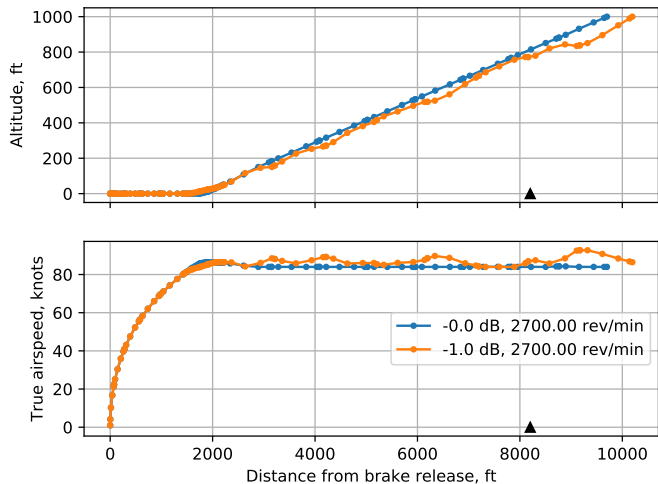
Instead of constraining OASPL at every trajectory point, we tried a derived acoustic metric similar to EPNL



Pseudo-EPNL smooths the acoustic constraint response with respect to RPM



Even with the pseudo-EPNL constraint, the optimizations still don't return the manual sweep results



What are our next steps?

- ▶ Try a shooting method, instead of the current pseudo-spectral approach?
- ▶ Replace pseudo-EPNL interpolation with least-squares curve fit?
- ▶ Any other ideas?

Thanks for your attention!

Special thanks to Jeff Berton (NASA Glenn) and Andrew Ning (BYU)!



References I

- [1] S. Andrew Ning. “A simple solution method for the blade element momentum equations with guaranteed convergence”. In: *Wind Energy* (2013), n/a–n/a. ISSN: 1095-4244. DOI: 10.1002/we.1636.
- [2] Leonard V. Lopes. “Compact Assumption Applied to Monopole Term of Farassat’s Formulations”. In: *Journal of Aircraft* 54.5 (2017), 1649–1663. DOI: 10.2514/1.c034048.
- [3] F. Farassat. “Linear Acoustic Formulas for Calculation of Rotating Blade Noise”. In: *AIAA Journal* 19.9 (1981), pp. 1122–1130. ISSN: 0001-1452. DOI: 10.2514/3.60051.
- [4] F. Farassat. *Derivation of Formulations 1 and 1A of Farassat*. Tech. rep. NASA/TM 2007-214853. Hampton, VA, United States: NASA Langley Research Center, 2007.

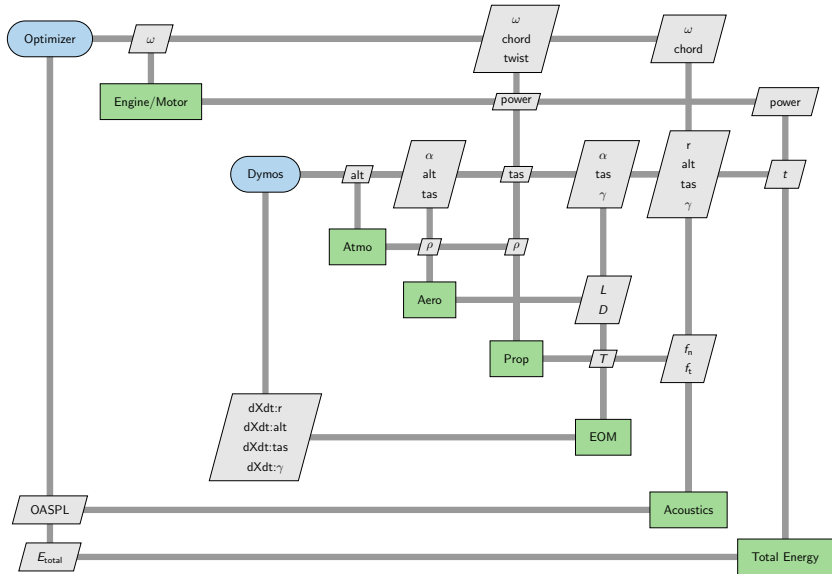


References II

- [5] Jeffrey J. Berton and Douglas M. Nark. “Low-Noise Operating Mode for Propeller-Driven Electric Airplanes”. In: *24th AIAA/CEAS Aeroacoustics Conference*. American Institute of Aeronautics and Astronautics, 2018.



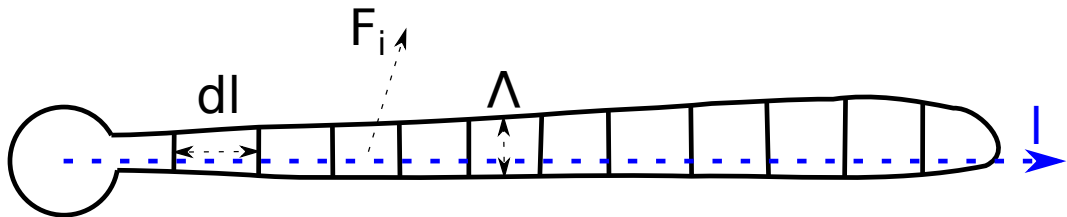
Extended Design Structure Matrix



Compact F1A

- ▶ Acoustic prediction method used here: compact version[2] of Farassat's 1A formulation[3, 4] of the FWH approach.
- ▶ **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.**