Simulation Based Case Study in Power-Optimal Geometric Morphing of Long-Tether Energy-Harvesting Kites

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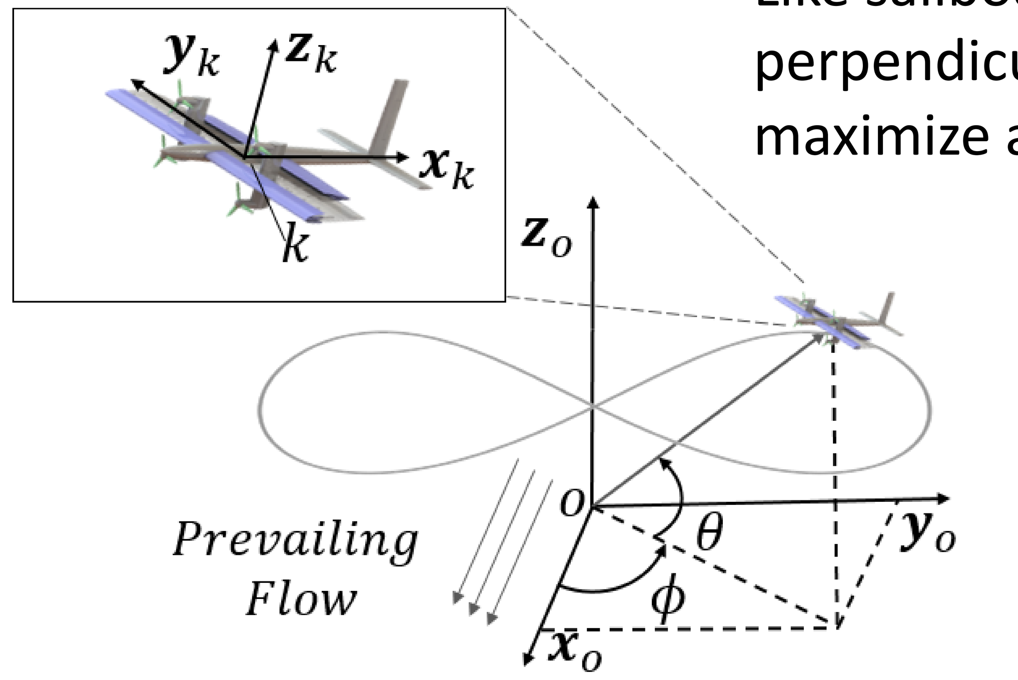
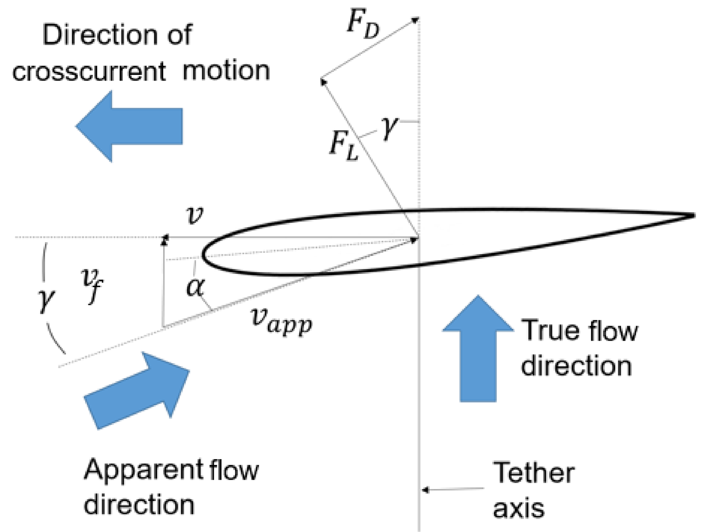
Background

Kites harvest energy from ocean currents with onboard turbines or through cyclic spooling over a figure-8 path

Like sailboats outpacing the wind, kites fly perpendicular to the prevailing flow to maximize apparent flow speed





$\vec{v}_{app} = \vec{v}_f - \vec{v}_{body} \longrightarrow Power \propto \|\vec{v}_{app}\|^3$

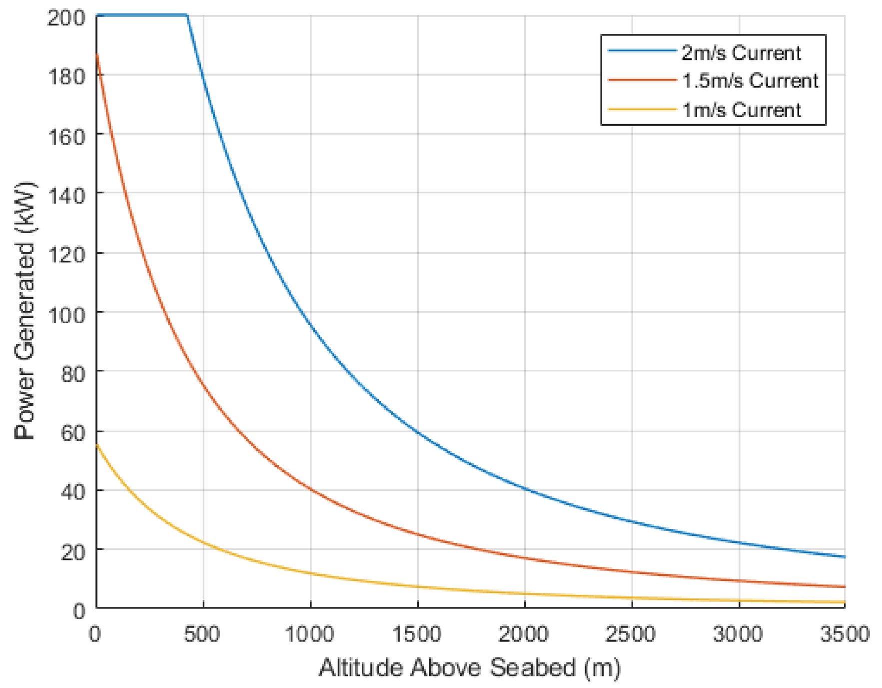
Small Increase in apparent speed = Large increase in power

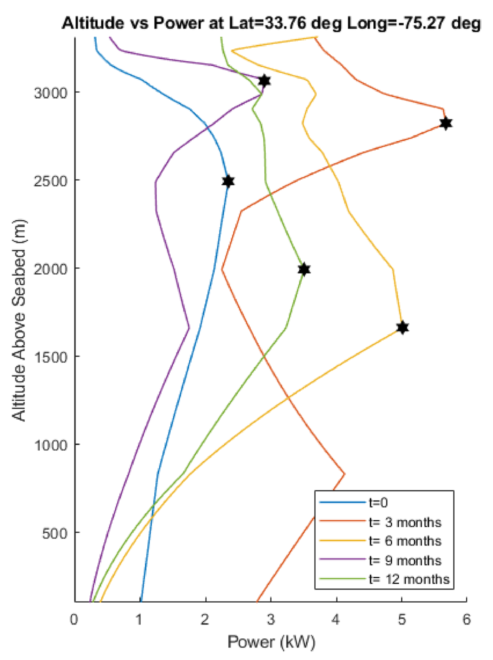
Critical Challenge

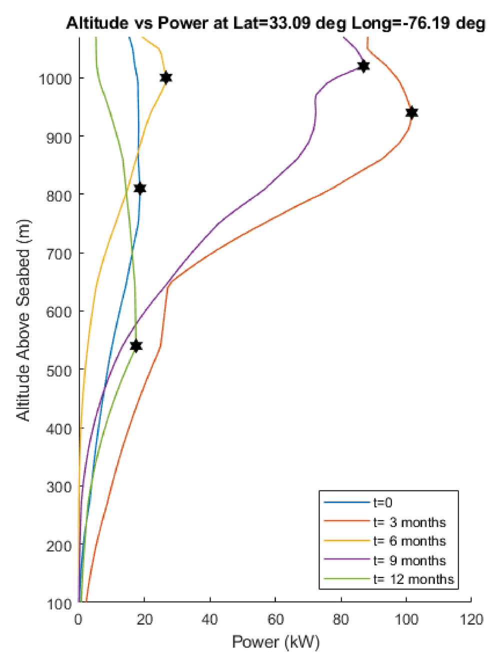
For a **<u>fixed</u>** kite geometry:

→Power is highly sensitive to tether length

→Stochastic flow resource causes optimal operating altitude/tether length to vary with time







Research Question: Can dramatically enhanced variable-altitude performance be realized with a kite that <u>morphs</u> with altitude variation?

The Math Behind Morphing

Power generation was modeled with quasi-static equations developed in [1]

$$P_{kite} = \frac{2}{27} C_l^3 \frac{\rho_{water}\left(v_{flow}\cos\theta\cos\varphi\right)^3}{C_{d,total}^2}\frac{A_{wing}}{A_{ref}} \longrightarrow P_{kite} \propto \frac{C_l^3}{C_{d,total}^2}$$

$$C_l = \gamma\alpha\frac{A_{wing}}{A_{ref}} \qquad C_{d,total} = \frac{1}{4}C_{d,thr}\frac{d_{thr}L_{thr}}{A_{ref}} + \left(C_{d,w0} + \frac{C_l^2}{AR e_d \pi}\right)\frac{A_{wing}}{A_{ref}} + C_{d,fuse}\frac{A_{fuse}}{A_{ref}}$$

Parameter	Symbol	Value	Unit
Kite Lift Coefficient	C_l	Varies	-
Kite Drag Coefficient	$C_{d,total}$	Varies	-
Angle of Attack	α	12	deg
Water Density	ρ_{water}	1000	kg/m^3
Reference Area	A_{ref}	16	m^2
Wing Area	A_{wing}	Varies	M^2
Flow Speed	v_{flow}	Varies	m/s
Kite Elevation	θ	30	deg
Kite Azimuth	φ	0	deg
Tether Drag Coef	$C_{d,thr}$	0.1	-
Tether Diameter	d_{thr}	12.5	mm
Tether Length	L_{thr}	Varies	m
Wing Drag at Zero Lift	$C_{d,w0}$	0.0065	-
Aspect Ratio	AR	Varies	-
Oswald Efficiency	e_d	0.92	-
Fuselage Drag Coef	$C_{d,fuse}$	0.04	-
Fuselage Area	A_{fuse}	0.28	m^2

At **long** tether lengths, this term (tether drag) dominates $C_{d,total}$

↓

Small changes in wing drag have little impact on $C_{d,total}$

↓

$\frac{C_l^3}{C_{d,total}^2}$ is maximized by *maximizing* C_l at the cost of added wind drag

At **short** tether lengths, this term (wing drag) dominates $C_{d,total}$

↓

Small changes in wing drag have a large impact on $C_{d,total}$

↓

$\frac{C_l^3}{C_{d,total}^2}$ is maximized by *minimizing* wing drag while sacrificing additional lift

A Mechanism for Morphing

At **low** altitudes/tether lengths the majority of drag in the system comes from the wings

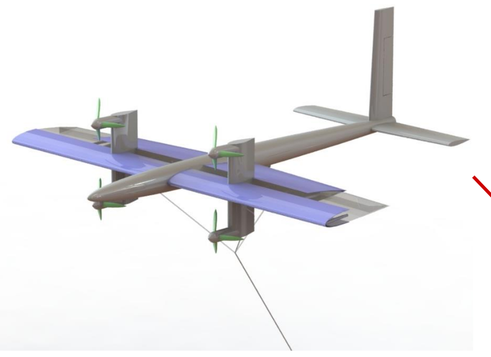
↓

A **smaller** and efficient wing is optimal!

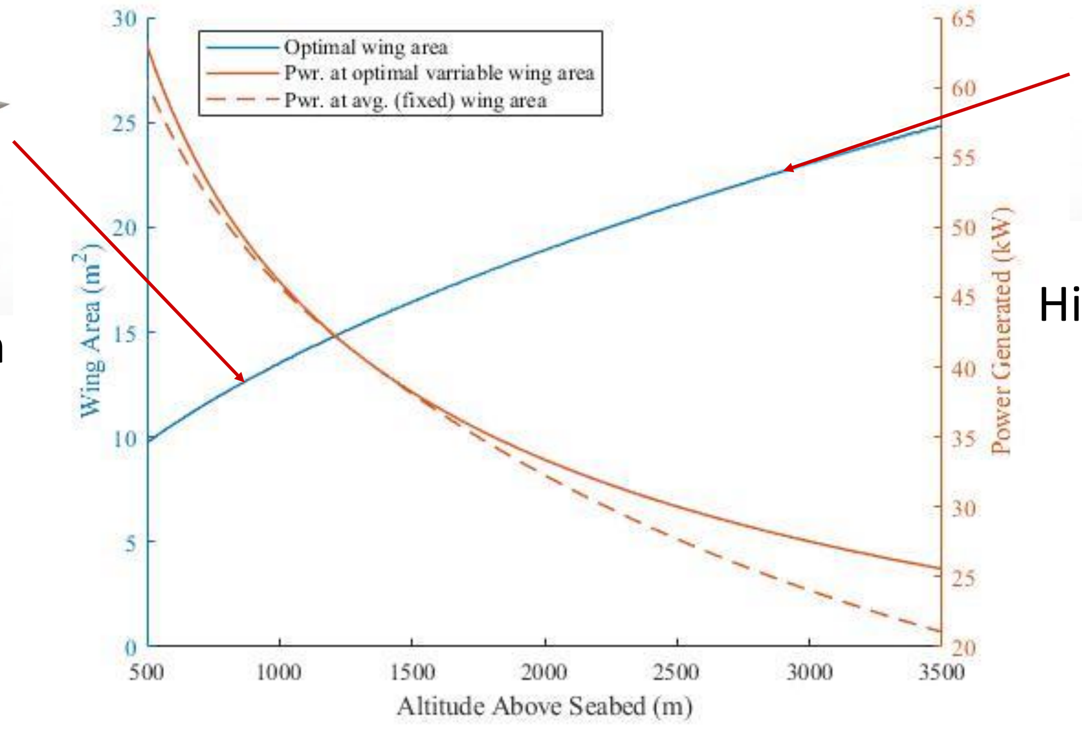
At **high** altitudes/tether lengths the majority of drag in the system comes from the tether

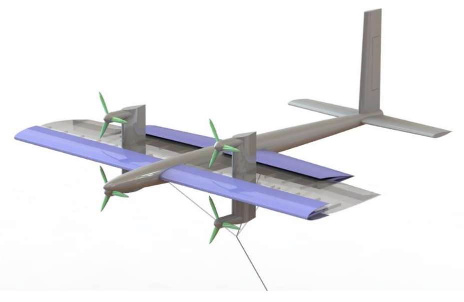
↓

A **larger** wing that sacrifices added drag for additional lift is optimal!



Low altitude design





High altitude design

Long-Term Performance Simulation

Performance of three kites was simulated over a year using MAB-SAB data

Kite 1→Fixed tether length with fixed wings

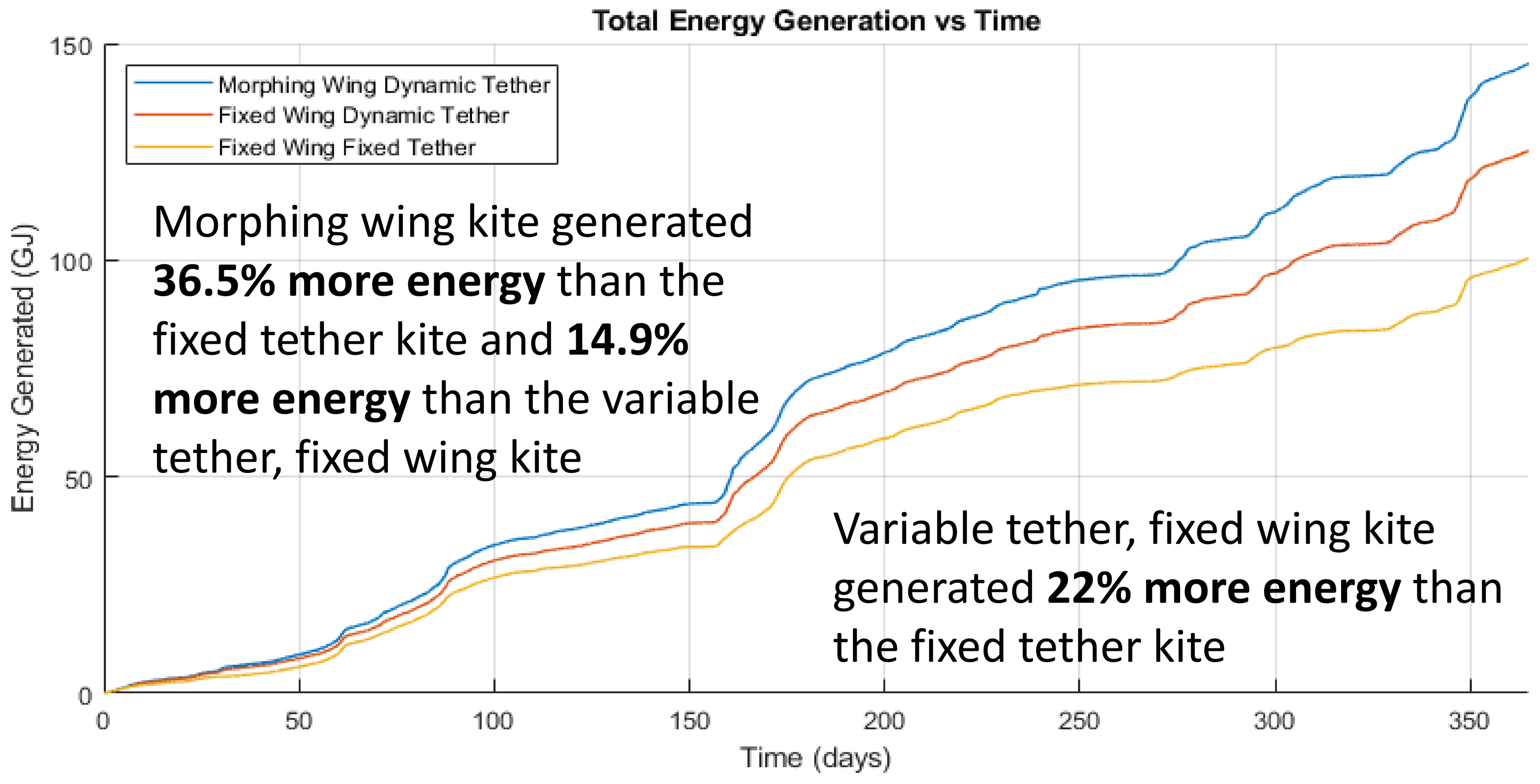
Kite 2→Variable tether length with fixed wings

Kite 3→Variable tether length with morphing wings

Variable parameters adjusted every 24 hours

Kites 2 and 3 adjusted tether length

Kite 3 also adjusted wing by morphing wing chord



Morphing wing kite generated **36.5% more energy** than the fixed tether kite and **14.9% more energy** than the variable tether, fixed wing kite

Variable tether, fixed wing kite generated **22% more energy** than the fixed tether kite

Future Work

1. Performance of a morphing kite will be modeled using the 6-DOF dynamic model developed in [2]
   i. High level predictive control strategies from [3] will be implemented
2. A 1/10th scale kite capable of morphing will be designed and fabricated
   i. The pool testing setup developed in [2] will be leveraged for this testing
3. Low level control techniques will be developed to maintain control of a morphing kite while maximizing power

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U.S. DEPARTMENT OF ENERGY

Coastal Studies Institute

DARPA

[1] M. Loyd, "Crosswind Kite Power," Journal of Energy, vol. 4, no. 3, pp. 106–111, 1980.

[2] Andrew Abney, James Reed, Kartik Naik, Sam Bryant, Dillon Herbert, Zak Leonard, Ashwin Vadlamannati, Mariah Mook, Sumedh Beknalkar, Miguel Alvarez, Kenneth Granlund, Matthew Bryant, Andre Mazzoleni, Hosam Fathy, and Chris Vermillion, "Autonomous Closed-Loop Experimental Characterization and Dynamic Model Validation of a Scaled Underwater Kite," Accepted February 2022 to *ASME Journal of Dynamic Systems, Measurement, and Control* – awaiting press.

[3] J. Fine, J. Reed, C. Vermillion, "Predictive Control of A Morphing Tethered Energy System," *Proceedings of the Conference on Control Technology and Applications*. Manuscript submitted for publication.