Dynamic Characterization, Flow Modeling, and Optimal Control of an Energy-Harvesting Underwater Kite in Realistic Ocean Conditions

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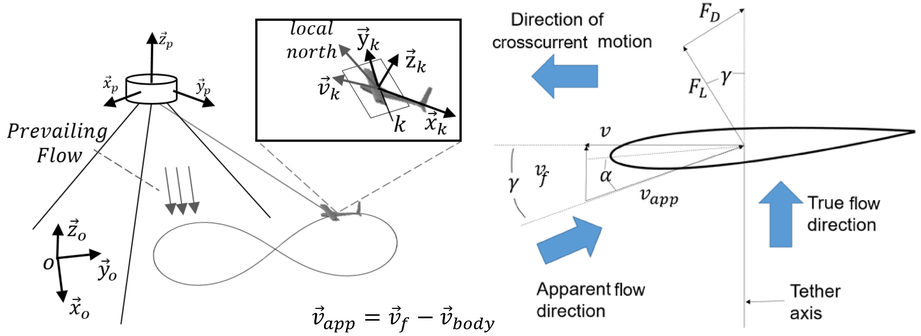
Objective: Take advantage of ocean currents to generate power
Approach: Design an energy harvesting kite-based system that flies perpendicular to the prevailing flow generating power from the apparent velocity.



$$\vec{v}_{app} = \vec{v}_f - \vec{v}_{body}$$

Kite follows figure-eight paths to generate power by flying perpendicular to the flow

Power From Kite System : $P_k \propto \|\vec{v}_{app}\|^3$

A little more flow = A *lot* more power

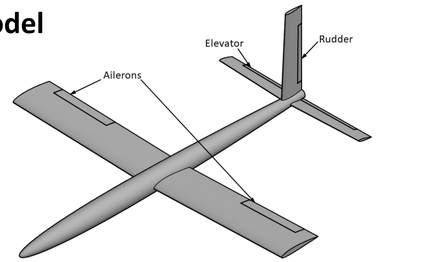
Our System Model

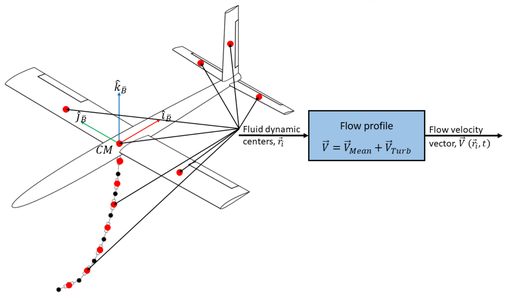
Dynamic Model

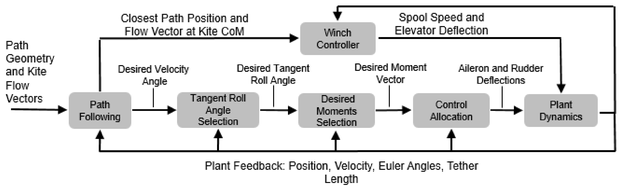
- Wing and stabilizer hydrodynamic coefficients characterized via AVL
- Hydrodynamic surfaces aggregated to characterize total forces and moments
- 6DOF lifting body and lumped mass tether

Environmental Model

- Spatial variation of flow is accounted for by applying local flow velocities at corresponding hydrodynamic centers
- Temporal variation is accounted for through modeled and observed data plus high-frequency turbulence and ocean waves



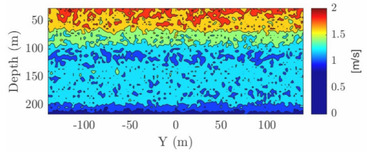




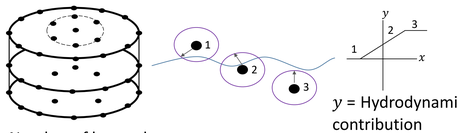
Path Following Controller

- Velocity Angle: Direction of velocity along a sphere of radius $||\vec{r}_{k/o}||$
- Tangent Roll Angle: Angle between the body Y-axis and the plane tangent to the sphere

Example of a **turbulent flow field** where the flow direction is into the page



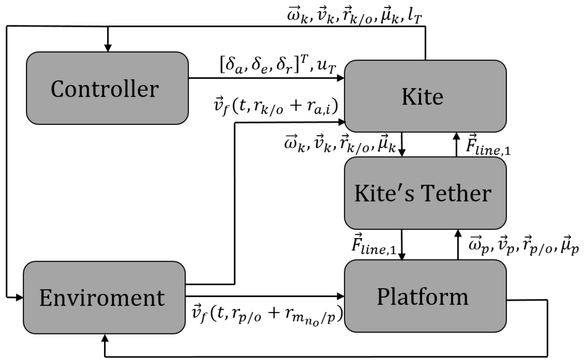
Deployment From Floating Platform



Number of lumped masses = N

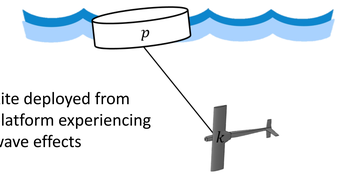
y = Hydrodynamic force contribution
x = Dist. from surface

- Platform is modeled in 6DOF using a lumped mass model
- Properties of each lumped mass
  - Radius
  - Projected areas A_x, A_y, A_z
  - Mass value = total mass / N
  - Buoyancy force = total buoyancy force / N



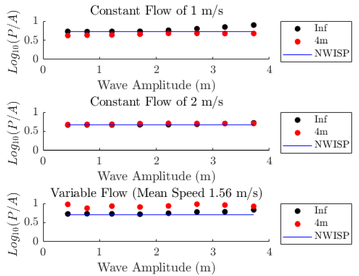
p = platform subscript
k = kite subscript
δ_a = aileron deflection
δ_r = rudder deflection
δ_e = elevator deflection
u_T =spool speed
$\vec{r}_{/o}$ = position vector
$\vec{v}$ = velocity vector
$\vec{\mu}$ = euler angles
$\vec{\omega}$ = angular velocity vec
l_t = tether length
$\vec{v}_f$ = flow velocity vector
$\vec{F}_{line,1}$ = tether tension

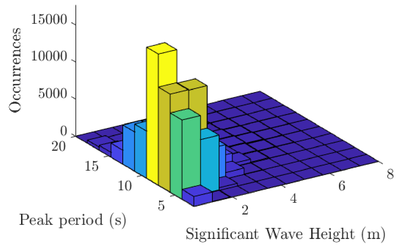
Kite and Platform in Ocean Waves



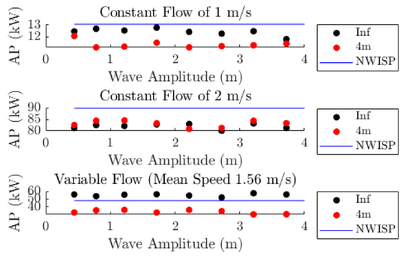
Kite deployed from platform experiencing wave effects

In common wave conditions, kite performance is shown to not significantly decrease in terms of average power (AP) or peak to average power ratio ($Log_{10}(P/A)$)



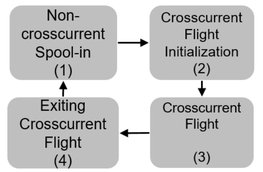


Histogram depicting wave conditions at CDIP 192 Oregon Inlet buoy over a seven year period



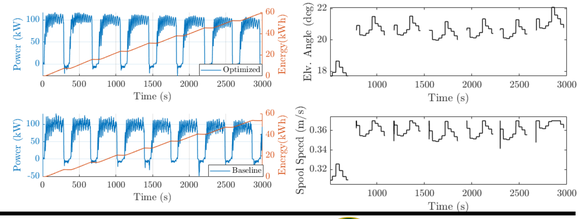
Power-optimal Control

Objective: Optimize the spool speeds, $u_T(t)$, and path elevation angle, $\phi(t)$, to maximize power in a variable flow environment.



Multi-cycle spooling transition controller

9.3 percent improvement in power production!



Maximize Cycle-Averaged Mechanical Power

Path center elevation angle and spooling profiles

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[1] J. Reed, J. Daniels, A. Siddiqui, M. Cobb, M. Muglia, and C. Vermillion, "Optimal cyclic control of an ocean kite system in a spatiotemporally varying flow environment."
[2] J. Reed, M. Cobb, J. Daniels, A. Siddiqui, M. Muglia, and C. Vermillion, "Hierarchical control design and performance assessment of an ocean kite in a turbulent flow environment,"IFAC-PapersOnLine,vol. 53, no. 2, pp. 12 726–12 732, 2020.
[3] D. J. Olinger and Y. Wang, "Hydrokinetic energy harvesting using tethered undersea kites, "Journal of Renewable and Sustainable Energy, vol. 7, no. 4, p. 043114, 2015.