Simultaneous Optimization of Geometric and Structural Wing Properties of an Underwater Energy Harvesting Kite

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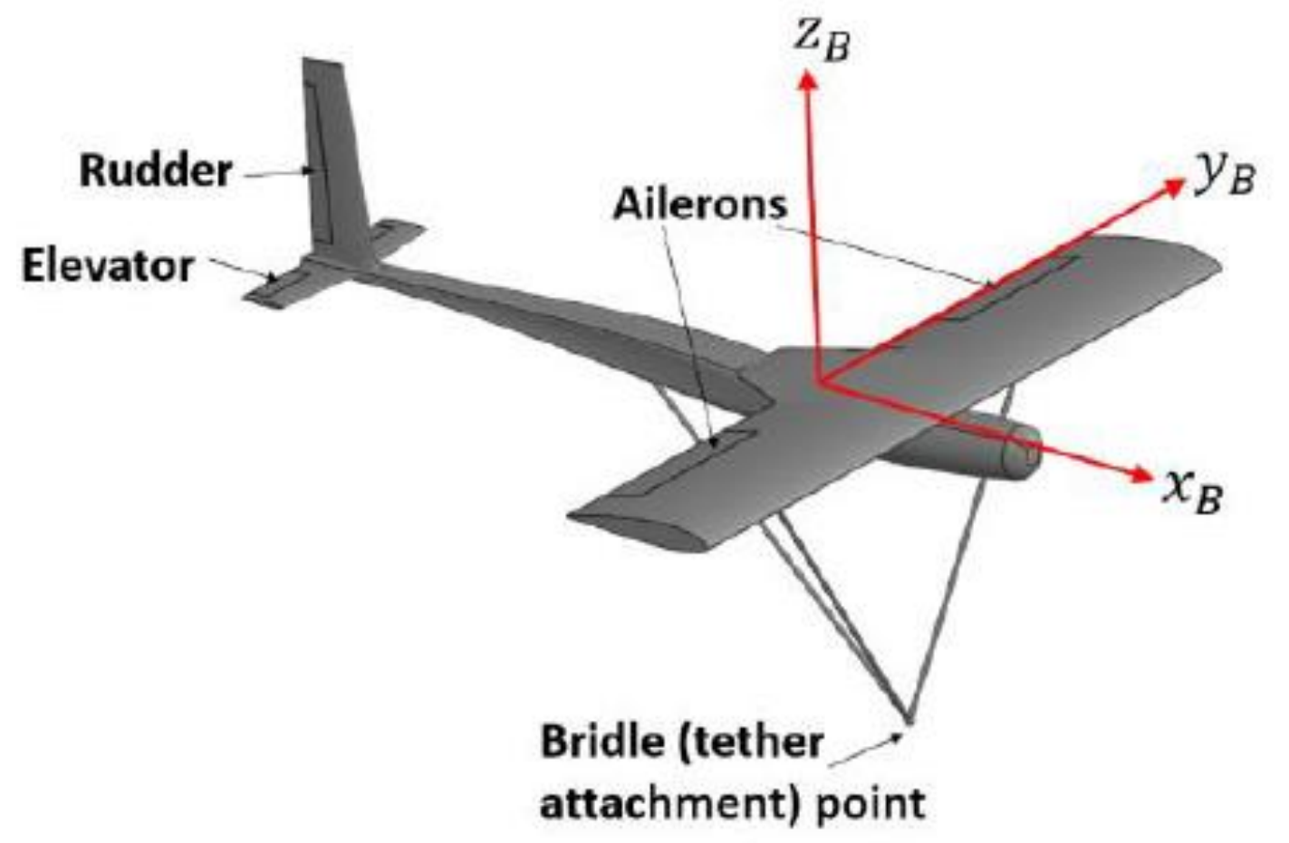
Principle of Operation

- A rigid, high lift/drag kite is spooled out in cross-current motions, resulting in high tether tension
- The kite is spooled in at a low angle of attach, resulting in low tension.
- Through the cyclic operation, net energy is generated at the mooring point



Overall optimization problem:

Simultaneous optimization of kite wing geometry and structure for maximizing power generated-to-wing mass ratio

Optimization problem formulation

$$\text{Objective:} \quad \max_{\boldsymbol{u}} \frac{P_{gen}}{m_{wing}}$$

$$\text{Subject to:} \quad P_{gen}(\boldsymbol{u}) \geq P_{req} \text{ (performance constraint)}$$

$$I_{xx}(\boldsymbol{u}) \geq I_{xx,req} \mid \delta_{max} \text{ (wing structural constraint)}$$

$$\boldsymbol{u} \in \{TR, \phi_w, \psi_w, \text{airfoil}, t_{sh}, N_{sp}, t_{sp1}, t_{sp2}, t_{sp3}, x_{sp1}, x_{sp2}, x_{sp3}, \}$$

Variables and Parameters

Variables

Geometric Variables

TR = Taper Ratio

ϕ_w = Twist Angle

ψ_w = Dihedral Angle

Structural Variables

N_{sp} = No. of spars

$t_{sp,i}$ = thickness of i^th spar

t_{sh} = wing shell thickness

$x_{sh,i}$ = location of i^th spar

Variables

P_{gen} = generated power

m_{kite} = kite structural mass

I_{xx} = Area moment of inertia

δ_{max} = max. wing tip deflection

α = angle of attack

Parameters

$t_{sh,f}$ = fuselage shell thickness

D = fuselage diameter

L = fuselage length

Optimization Modules

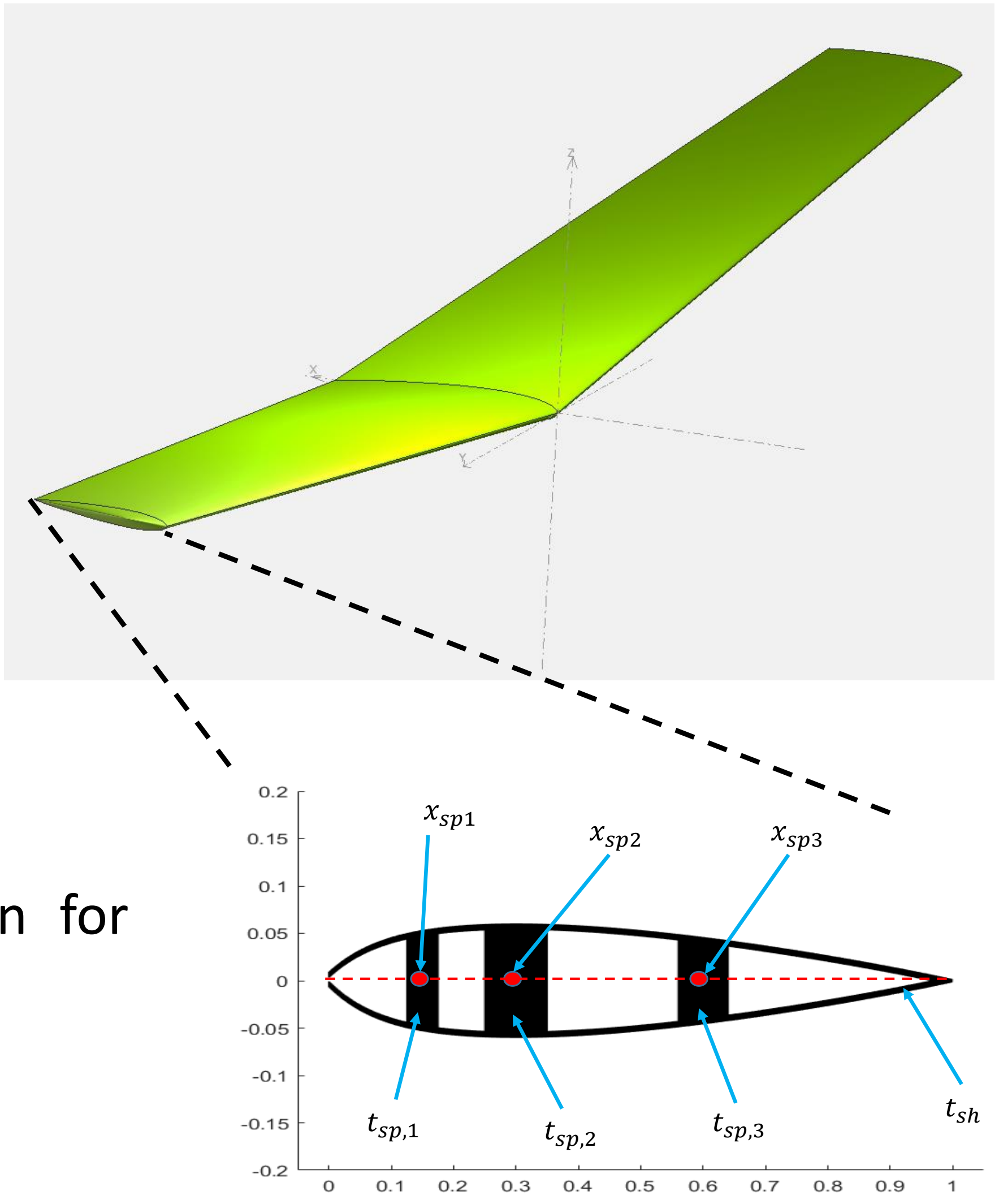
Overall optimization problem divided into 2 modules

Steady Flight Optimization Tool (SFOT)

Selects wing TR, ϕ_w, ψ_w to maximize power generation for optimal α or range of α in the vicinity of optimum α

Structural Wing Design Tool (SWDT)

Selects shell thickness, number of spars, and thickness and location of each spar to minimize wing mass, subject to wing tip deflection



Sample output from SWDT, showing structural wing design decision variables.

Effect of Wing Geometry on CL, CD, Cm

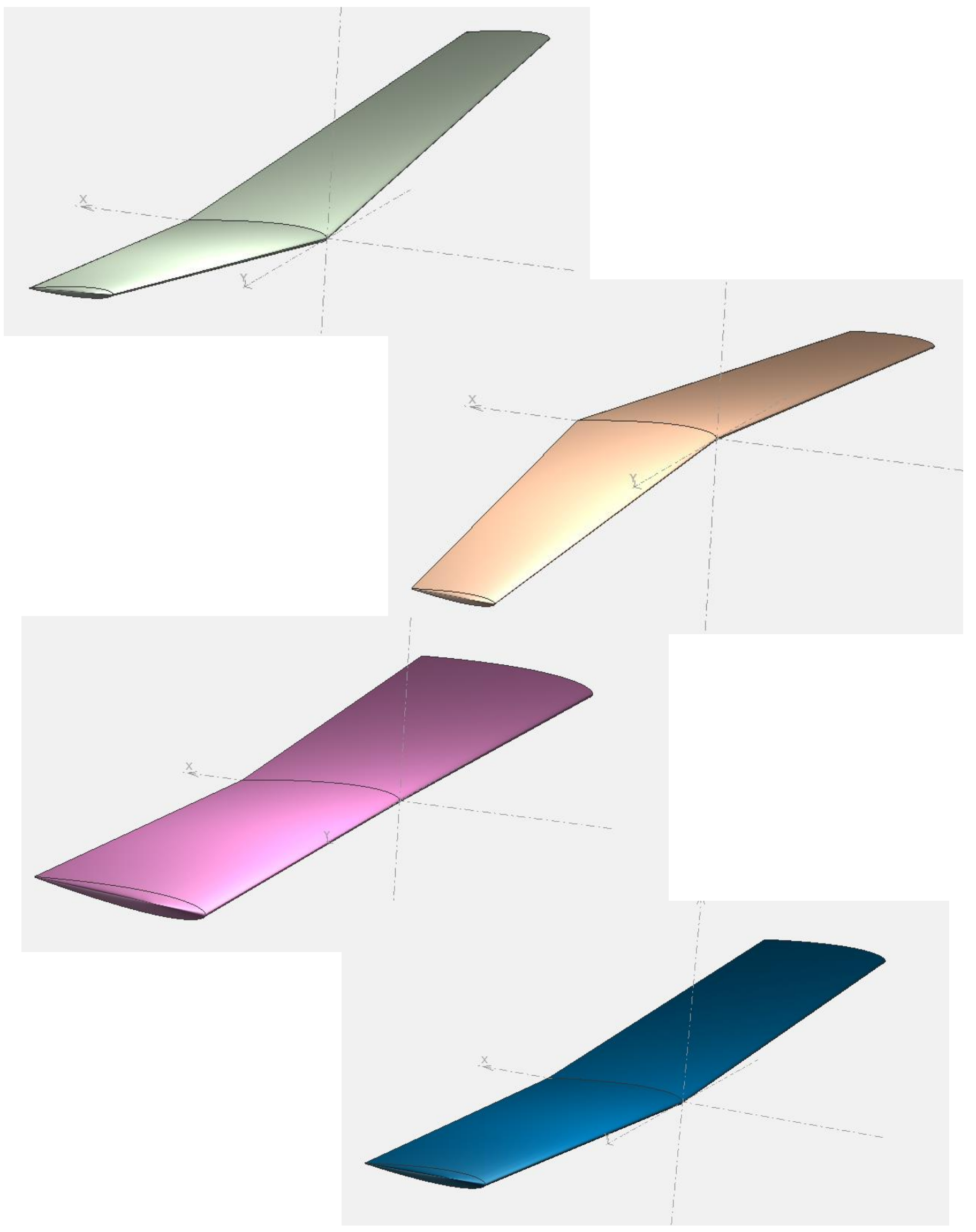
XFLR5 data acquisition and interpolation

- The effect of changing wing geometric variables was captured through batch analyses in XFLR5.
- A parametric sweep was performed using:

1. TR ∈ [0.6, 0.75, 0.9, 1.0, 1.1]
2. ϕ_w ∈ [-5, -3, 0, 3, 5]
3. ψ_w ∈ [-3, 0, 3, 6]
4. Airfoils: NACA0012, NACA0015, NACA2412, NACA4415

for a range of α and hydrodynamic coefficient C_L,C_D, and C_m data was collected

- A Multi-Dimensional Interpolation algorithm was used to interpolate data between the sweep points to make the design space continuous
- The hydrodynamic data was used in the SFOT module to calculate generated and optimal α



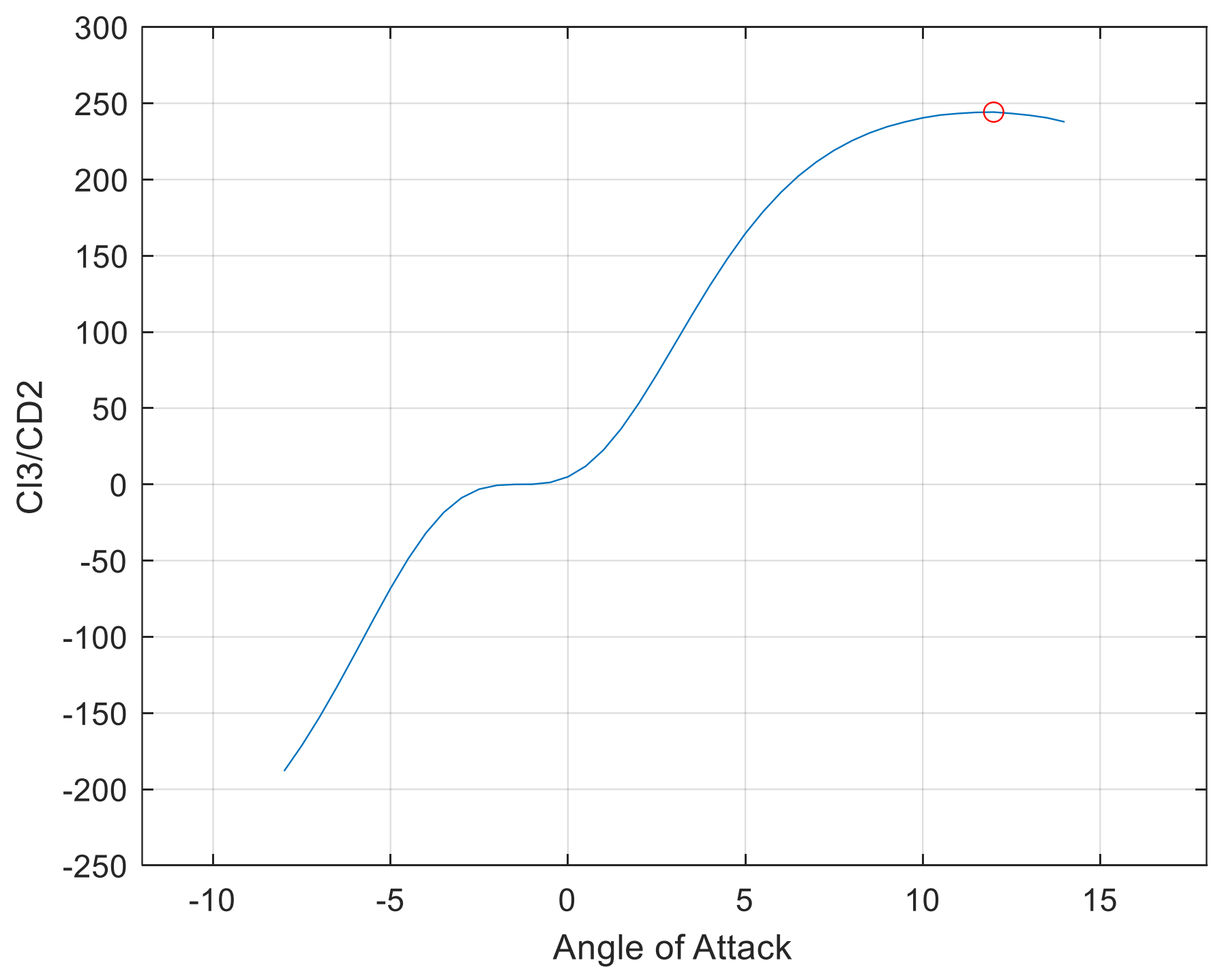
Angle of Attack and Generated Power

Effect of Angle of Attack (α) on SFOT module

- The objective of SFOT module is maximizing generated power given by Loyd (1980):

$$P_{gen} = \eta \cdot \left(\frac{2}{27}\right) \rho S_{ref} v^3 \left(\frac{C_L^3}{C_D^2}\right)$$

- For a fixed reference area (S_{ref}), flow velocity (v), fluid density (ρ), and efficiency factor (η), the generated power is a function of $\frac{C_L^3}{C_D^2}$
- The plot of $\frac{C_L^3}{C_D^2}$ vs α shows that $\frac{C_L^3}{C_D^2}$ reaches a maximum value at a single value of α which is the optimal angle of attack
- The corresponding values of design variables offer optimal flight dynamics under steady flight conditions (at optimal α), the kite operates across a range of angles of attack while performing figure-8 motions.
- A higher fidelity solution could be achieved while considering a range of α in the vicinity of optimal α and averaging the cumulative power generated



Optimization Results

Objective: Maximize Power-to-Weight ratio

Power Constraints:

1. $v = 1.5\ m/s,\ P_{req} = 100\ mW$
2. $v = 2.0\ m/s,\ P_{req} = 150\ mW$

Baseline (with optimal α)

	1.5 m/s		2.0 m/s	
Airfoil	P_{gen}	m_{wing}	P_{gen}	m_{wing}
NACA0012	**126.3**	**2321**	**-**	**-**

Optimal α, v = 1.5 m/s

Airfoil	P_{gen}	m_{wing}	TR	ϕ_w	ψ_w	tsh	Nsp	$tsp1$	$tsp2$	$tsp3$
NACA0012	**207.6**	**613.8**	**1**	**-0.181**	**0.1**	**0.00065**	**2**	**0.0**	**0.192**	**0.003**
NACA0015	**255.4**	**769**	**0.9**	**0.0**	**-3**	**0.0008**	**3**	**0.002**	**0.197**	**0.004**

Optimal α, v = 2.0 m/s

Airfoil	P_{gen}	m_{wing}	TR	ϕ_w	ψ_w	tsh	Nsp	$tsp1$	$tsp2$	$tsp3$
NACA0012	**433.7**	**930**	**1.1**	**0**	**-2.39**	**0.0007**	**1**	**0.0**	**0.2**	**0.0**
NACA0015	**439.2**	**798**	**1.1**	**1.672**	**-2.8**	**0.0001**	**2**	**0**	**0.199**	**0.147**

Range of α in the vicinity of optimal α, v = 2.0 m/s

Airfoil	P_{gen}	m_{wing}	TR	ϕ_w	ψ_w	tsh	Nsp	$tsp1$	$tsp2$	$tsp3$
NACA0012	**320.1**	**581.5**	**0.97**	**-0.57**	**0**	**0.0001**	**1**	**0**	**0.192**	**0**
NACA0015	**392**	**737.3**	**0.884**	**-1**	**0**	**0.001**	**3**	**0.002**	**0.192**	**0.0147**

Conclusion

Improved performance: Higher power-to-weight ratio

- The combined optimization of geometric and structural properties of the wing results in a significantly higher techno-economic metric: power generated-to-weight ratio, compared to the baseline model

Optimal α vs Range of α

- A marginally improved performance is observed when cumulative power averaged over a range of α is used in SFOT instead of power generated at optimal α. Further investigation needs to be carried to observe the effect of α range.

Future work

Increase fidelity of optimization: Increase fidelity and accuracy of optimization method by:

1. Including fuselage properties (such as diameter, length, thickness) as decision variables
2. Adding wing and stabilizer locations, and tether attachment point as decision variables
3. Including longitudinal stability analysis as part of optimization

Validation using dynamics simulations

This will involve validating enhanced performance of the derived kite designs using simulations where the kite will execute figure-8 motions while spooling out followed by spooling in at low tension