Power Curve and Design Optimization of Drag Power Kites

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October 5th, 2017,
Airborne Wind Energy Conference 2017, Freiburg, Germany
How does an optimal drag power kite look like?
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... and what are the sensitivities of design parameters?
Outline

1. Model Derivation
2. Power Curve Optimization
3. Design Parameter Optimization
4. Parameter Studies
5. Conclusions
Kinematics
Assumption 1: Loyd’s model (extended)
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\[ v_a = \cos(\varphi) \cos(\vartheta) v_w \frac{\sqrt{C_L^2 + (C_{D,eq} + C_{D,rot})^2}}{C_{D,\Sigma}} \]
Assumption 1: Loyd’s model (extended)

\[ v_a = \cos(\varphi) \cos(\vartheta) v_w \frac{\sqrt{C_L^2 + (C_{D,eq} + C_{D,rot})^2}}{C_{D,\Sigma}} \]

Assumption 2: azimuth and elevation are constant “effective” values
(a) Angle of attack changed. (b) Flaperon angle changed.
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(b) Flaperon angle changed.

\[ c_L \text{ vs. } c_D \]

- CFD result
Assumption 3: quadratic approximation

\[ c_D = c_{D,0} + c_{D,2}c_L^2 \]
Assumption 4: thin airfoil

\[ C_L = \frac{c_L}{1 + \frac{2}{AR}} \quad \text{with} \quad AR = \frac{b^2}{A} \]

\[ C_{D,k} = c_D + \frac{C_L^2}{\pi e AR} \]

\[ C_{D,k,i} \]
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\[ C_{D,k} = c_D + \frac{C_L^2}{\pi e AR} + C_{D,k,a} + C_{D,k,o} + C_{D,k,i} \]

Assumption 4: thin airfoil

\[ C_L = \frac{c_L}{1 + \frac{2}{AR}} \quad \text{with} \quad AR = \frac{b^2}{A/n_{mw}} \]

\[ C_{D,k} = c_D + \frac{C_L^2}{\pi e AR} + C_{D,k,a} + C_{D,k,o} \]

Assumption 5: no interaction between wings and rotors

**Assumption 6:** wind contribution on airspeed negligible along tether length

→ After conversions: \[ C_{D,te} = \frac{1}{4} \frac{d_{te} L_{te}}{A} c_{D,te} \]

mechanical load carrier (core)
electrical load carrier/electrical cable:
  litz wire (±)
  insulator
  grounded shield
electrical cable jacket
room for communication cables
tether jacket
Mechanical strength: \( F_{te,\text{max}} \sim A_{te,\text{core}} \)

Electrical resistance:
\[
R_{te,\text{wire}} \sim \frac{L_{te}}{A_{te,\text{wire}}} \\
R_{te} = \frac{R_{te,\text{wire}}}{n_{te,c,+}} + \frac{R_{te,\text{wire}}}{n_{te,c,-}}
\]

Dielectric strength: \( E_{te,\text{ins}} = f(U_{te,n}, r_{\text{wire}}, w_{\text{ins}}) \)

Total diameter, mass: [straight-forward summation]

Feasibility condition: [no overlapping electrical cables]
“Aerodynamic” power:

\[ P_a = \frac{1}{2} \rho A v_a^3 C_{D,\text{rot}} \]
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**Assumption 7:** actuator disk

Single rotor:
\[ F_{\text{rot},s} = 2\rho A_{\text{rot},s} v_a^2 a(1 - a) \]
\[ P_{\text{rot},s} = 2\rho A_{\text{rot},s} v_a^3 a(1 - a)^2 \]
"Aerodynamic" power: \[ P_a = \frac{1}{2} \rho A v_a^3 C_{D,rot} \]

**Assumption 7:** actuator disk

After conversions:

\[ C_{D,rot} = 4 \frac{n_{rot} A_{rot,s}}{A} r_{rot} a (1-a) \quad \text{and} \quad \eta_{a,+} = 1-a \]

Single rotor:

\[ F_{rot,s} = 2 \rho A_{rot,s} v_a^2 a (1-a) \]
\[ P_{rot,s} = 2 \rho A_{rot,s} v_a^3 a (1-a)^2 \]
Kinematics

Aerodynamics

Tether

Rotors

Kite

Power Conversions

42.83 kWh
\[ \begin{align*}
 P_a & \rightarrow \eta_a \eta_{rot} \leftarrow P_{rot} \\
 \eta_s & \leftarrow P_s \rightarrow \eta_m \\
 \eta_{m} & \leftarrow P_{el,m} \rightarrow \eta_{pe,k} \\
 \eta_{te} & \leftarrow P_{el,k} \rightarrow \eta_{pe,g} \\
 P_{el} & \rightarrow \eta_{pe,g} \leftarrow P_{el,g}
\end{align*} \]

- rotor(s)
- shaft(s), gears(s)
- el. machine(s)
- kite power electronics (incl. LV-HV)
- tether
- ground power electronics, possibly transformer (incl. LV-HV)
$\eta_{a,+} = 1 - a$

$P_a \rightarrow \eta_a \eta_{\text{rot}} \rightarrow \eta_s \rightarrow \eta_m \rightarrow \eta_{\text{pe,k}} \rightarrow \eta_{\text{te}} \rightarrow \eta_{\text{pe,g}} \rightarrow P_{\text{el}}$

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![Diagram showing power flow](image)

\[ P_{a} \rightarrow \eta_{a}\eta_{rot} \rightarrow \eta_{s} \rightarrow \eta_{m} \rightarrow \eta_{pe,k} \rightarrow \eta_{te} \rightarrow \eta_{pe,g} \rightarrow P_{el} \]

- **Rotor(s)**
- **Shaft(s), gears(s)**
- **Electrical machine(s)**
- **Kite power electronics (incl. LV-HV)**
- **Tether**
- **Ground power electronics, possibly transformer (incl. LV-HV)**

Via:

\[ P_{te-loss} = R_{te}I_{te}^2 \]
Assumption 8: constant efficiency factors for others
Assumption 9: logarithmic wind shear

\[ v_w = v_{w,ref} \frac{\ln \left( \frac{h}{z_0} \right)}{\ln \left( \frac{h_{ref}}{z_0} \right)} \quad \text{with} \quad h = h_{to} + L_{te} \sin(\vartheta) \]

Assumption 10: Rayleigh distribution

\[ p(v_{w,ref}) = \frac{v_{w,ref}}{\bar{v}_{w,ref}^2} \exp \left( -\frac{v_{w,ref}^2}{2\bar{v}_{w,ref}^2} \right) \]
Assumption 11: launch & landing energy consumption negligible
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Year energy yield: 

\[
E_{\text{el, yr}} [\text{Wh/yr}] = \frac{8,760 \text{ h}}{1 \text{ yr}} \cdot \int_{0}^{\infty} p(v_w, h_{\text{ref}}) \cdot P_{\text{el}, +}(v_w, h_{\text{ref}}) \, dv_{w, h_{\text{ref}}}
\]
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Year energy yield: \[ E_{\text{el, yr}}[\text{Wh/yr}] = \frac{8,760 \text{ h}}{1 \text{ yr}} \cdot \int_{0}^{\infty} p(v_{w, h_{\text{ref}}}) P_{\text{el,+}}(v_{w, h_{\text{ref}}}) dv_{w, h_{\text{ref}}} \]

LCOE:

\[ k_{\text{LCOE}} = \frac{k}{E_{\text{el, yr}}} \]
**Assumption 11:** launch & landing energy consumption negligible

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\[ k_{\text{LCOE}} = \frac{k}{E_{\text{el, yr}}} \]

**Yearly costs:**

\[ k = k_{\text{inv}} + k_{\text{op}} \]

\[ k_{\text{inv}} = K_{\text{inv}} \frac{I(1 + I)^{T/yr}}{(1 + I)^{T/yr} - 1} \]

\[ k_{\text{op}} = I_{\text{op}} K_{\text{inv}} \]
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Year energy yield: \[ E_{el, yr}[\text{Wh/yr}] = \frac{8,760 \text{ h}}{1 \text{ yr}} \cdot \int_{0}^{\infty} p(v_{w, h_{ref}})P_{el,+}(v_{w, h_{ref}})dv_{w, h_{ref}} \]

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\[ k_{inv} = K_{inv} \frac{I(1 + I)^{T/yr}}{(1 + I)^{T/yr} - 1} \]
\[ k_{op} = I_{op}K_{inv} \]

Total capital costs:
\[ K_{inv} = k_{dt}P_{el,n-ins} + K_{inv,o&p} \]
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2. **Power Curve Optimization**
3. Design Parameter Optimization
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Assumption 12: \( \forall v_w, h_{\text{ref}} \in [0, v_w, h_{\text{ref, cut-out}}] : \arg \{ \max_u P_a \} \approx \arg \{ \max_u P_{\text{el}} \} \)
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Assumption 13: \( \sqrt{C_L^2 + C_{D,\Sigma}^2} \approx C_L \)
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\[ \text{power} \]

\[ \text{wind speed} \]
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1. Model Derivation
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Key ideas
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- serious estimates/better models for *investment costs of other parts/profit margin*
- as well as for *mass*: not possible/too hard
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⇒ INSTEAD: compute "\textit{maximum allowed}" \textit{investment costs} and "\textit{maximum allowed}" \textit{mass} as result, which are requirements for detailed design
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- rearrange equations into sequence of explicit analytical equations
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Optimization problem:

\[
\max_y \frac{\hat{K}_{\text{inv,o&p}}}{A} \\
\text{s.t. } y \leq y \leq \bar{y}
\]
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\[ P_{a}, P_{el} \text{ [MW]} \]

 Minor axis:

- \( P_{a} \) and \( P_{el} \) are plotted against the abscissa.

- The graph shows four distinct regions labeled I(a), I(b), II, III(a), III(b), and IV.

- Region III(b) is highlighted with a label indicating an approximation:

  \[ \approx 90 \text{ kW/m}^2 \]
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<thead>
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- A (low) tower might cover more than its own cost.
- For offshore, the maximum allowed cost is more than the double.
- The technology is scalable: the larger the system, the higher the power density and maximum allowed cost.
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- tether material selection and nominal voltage have almost no effect
- high airfoil lift and high wing loading are required for high maximum allowed cost and a high power density
- wide Region III(a) enables much lower wing loading and higher maximum allowed cost
- a (low) tower might cover more than its own cost
- for offshore, the maximum allowed cost is more than the double
- the technology is scalable: the larger the system, the higher the power density and maximum allowed cost
- the model can reproduce measured data by Makani (model verification, at least in part)
Outline

1. Model Derivation
2. Power Curve Optimization
3. Design Parameter Optimization
4. Parameter Studies
5. Conclusions
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Outlook:

- my dissertation/our papers: all details and additional enhancements
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- can reproduce measurements by Makani
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Outlook:

- my dissertation/our papers: all details and additional enhancements
- airfoil optimizations
- verifications: wind tunnel, higher fidelity models, tiny-scale (1 kW) kite on the way, small-scale (20 kW) kite planned
Power Curve and Design Optimization of Drag Power Kites

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October 5th, 2017,
Airborne Wind Energy Conference 2017, Freiburg, Germany