Recovery Phase Analysis of a Pumping Kite Wind Generator

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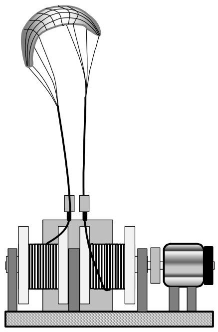

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AWEC 2015, Delft, 15th-16th of June 2015

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Outline

- Introduction
- Modelling
  - Lift and drag
  - Dynamic and steady-state model
- Approaches
  - Fly to zenith
  - Pitch and pull
  - Free and pull
- Examples
- Conclusions

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Introduction

Pumping-kite power generation

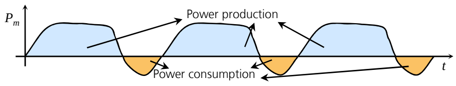
consists of two phases

- generation phase
- consumption phase

The success of the approach is based on the fact

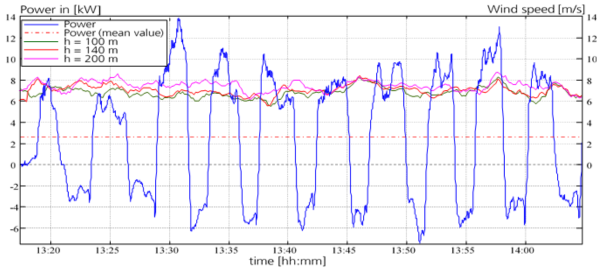
- consumption phase is economic in time and power
  - short time comparing with the generation phase
  - the energy consumption of the electric machine is low

Schematic concept



Introduction

Experimental data



Optimization is possible, but where is the limit….

- to obtain a simple model for the estimation
- to set some assuptions
- to study the most common approaches
- to calculate same examples

Modelling

- Assumptions
  - Possible control of angle of attack at zero lift
  - Generator/motor with identical power curve
  - Recovery starts without dead time
- Modelling
  - Estimation for lift and drag coefficients
  - Dynamic model
  - Steady-state model

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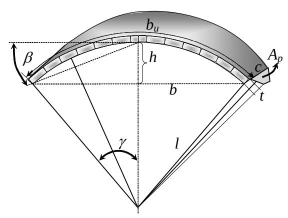
Modelling: Aerodynamic Coefficients

- For the ram-air kite
  (following Lingard 1995)



A: kite surface
Λ: aspect ratio
α: angle of incidence
α_{ZL}: angle of incidence for zero lift
a_0: 2D lift curve slope

$$c = \sqrt{A/\Lambda} \quad b_u = \sqrt{A\Lambda}$$

Lift coefficient for the kite

$$C_{Lk} = C_L + C_{Lc}$$

$$C_L = a(\alpha - \alpha_{ZL}) \cos^2 \beta$$

$$C_{Lc} = k_1 \sin^2(\alpha - \alpha_{ZL}) \cos(\alpha - \alpha_{ZL})$$

$$a = \frac{\pi a_0 k \Lambda}{\pi \Lambda + a_0 k (1+\tau)} \quad k = \frac{2\pi\Lambda}{a_0} \tanh \frac{a_0}{2\pi\Lambda}$$

$$k_1 = \begin{cases} 3{,}33 - 1{,}33\Lambda & 1 < \Lambda < 2.5 \\ 0 & \Lambda > 2.5 \end{cases}$$

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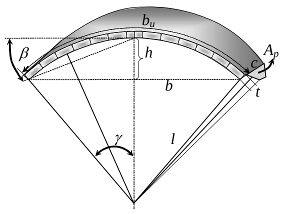
Modelling: Aerodynamic Coefficients



A: kite area
A_p: area of stabilizer
Λ: aspect ratio
α: angle of incidence
α_{ZL}: angle of incidence for zero lift
a_0: 2D lift curve slope

Drag coefficient for the kite

C_{Dk} = profile drag + induced drag + drag of lines

Induced drag

$$C_{iD} = \frac{a^2(\alpha-\alpha_{ZL})^2(1+\delta)}{\pi\Lambda} + k_1 \sin^3(\alpha-\alpha_{ZL})$$

δ is a small factor to allow for non-elliptic loading

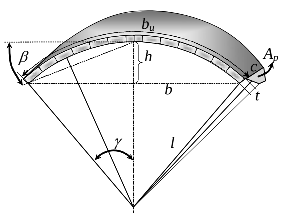
Profile drag

$$C_{D0} = C_{Dba} + C_{Dfr} + C_{Dsp} + C_{Dan}$$

- Basic airfoil drag (for typical section): $C_{Dba} \approx 0.015$
- Surface irregularities and fabric roughness: $C_{Dfr} \approx 0.014$
- Open airfoil nose: $C_{Dan} \approx 0.5t/c$
- Drag of pennants and stabilizer panels: $C_{Dsp} \approx 0.5A_p/b_u c$

$$C_{D0} = 0.029 + 0.5(A_p/b_u c + t/c)$$

Modelling: Aerodynamic Coefficients



Drag of lines

$$C_{Dlines} = \frac{n_\ell d_\ell l \cos^3\alpha}{b_u c}$$

n_ℓ: number of lines
d_ℓ: diameter of a line
l: mean line length
$b_u c$: kite area
α: angle of incidence

Store drag

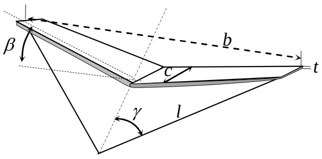
$$C_{Ds} = \frac{\text{store drag area}}{b_u c} \approx 0.006$$

Total drag

$$C_{Dk} = C_{D0} + C_{Ds} + \frac{a^2(\alpha-\alpha_{ZL})^2(1+\delta)}{\pi\Lambda} + k_1\sin^3(\alpha-\alpha_{ZL}) + \frac{0.5A_p + n_\ell d_\ell l \cos^3\alpha}{b_u c}$$

Modelling: Aerodynamic Coefficients

For a wing
(following Hoerner 1965)



A: kite surface
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α_{ZL}: angle of incidence for zero lift
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$$c = \sqrt{A/\Lambda} \quad b = \sqrt{A\Lambda}$$

Lift coefficient for the kite

$$C_{Lk} = C_L + C_{Lc}$$

$$C_L = a(\alpha - \alpha_{ZL})\cos^2\beta$$

$$C_{Lc} = k_1 \sin^2(\alpha - \alpha_{ZL})\cos(\alpha - \alpha_{ZL})$$

$$a = \frac{\pi a_0 k \Lambda}{\pi \Lambda + a_0 k(1+\tau)} \quad k = \frac{2\pi\Lambda}{a_0}\tanh\frac{a_0}{2\pi\Lambda}$$

$$k_1 = \begin{cases} 3{,}33 - 1{,}33\Lambda & 1 < \Lambda < 2.5 \\ 0 & \Lambda > 2.5 \end{cases}$$

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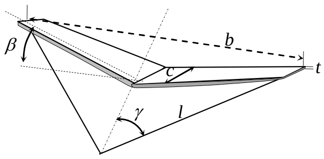
Modelling: Aerodynamic Coefficients



Drag coefficient for the wing

$$C_{Dk} = \text{profile drag} + \text{induced drag} + \text{drag of lines}$$

Induced drag

$$C_{iD} = \frac{a^2(\alpha - \alpha_{ZL})^2(1+\delta)}{\pi\Lambda} + k_1 \sin^3(\alpha - \alpha_{ZL})$$

δ is a small factor to allow for non-elliptic loading

Profile drag

$$C_{D0} = C_{Dba} + C_{Dan}$$

- Basic airfoil drag (for typical section): $C_{Dba} \approx 0.015$
- Open airfoil nose: $C_{Dan} \approx 0.5t/c$

$$C_{D0} = 0.015 + 0.5t/c$$

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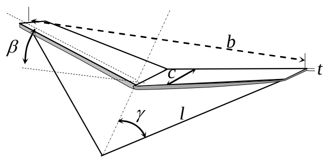
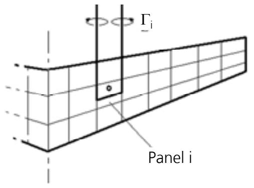
Modelling: Aerodynamic Coefficients





- For a wing (other approach)
  (Jae Lim 2015)

  Vortex lattice method and the Kutta-Joukowski theorem

  Lift coefficient for the wing

  $$F_{L_i} = \rho V \Gamma_i b_{panel} \quad F_L = \sum_{i=1}^{n} F_{L_i} \quad C_L = \frac{F_L}{0.5 \rho V^2 A}$$

  Drag coefficient for the wing

  $$F_{D_i} = \rho V \Gamma_i \sin(\alpha_{twist} - \alpha_{panel}) \quad F_D = \sum_{i=1}^{n} F_{D_i}$$

  $$C_{iD} = \frac{F_D}{0.5 \rho V^2 A} + k_1 \sin^3(\alpha - \alpha_{ZL})$$

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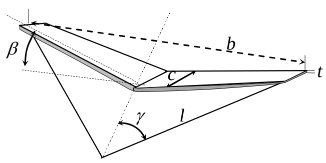
Modelling: Aerodynamic Coefficients



Drag of lines

$$C_{Dlines} = \frac{n_\ell d_\ell l \cos^3 \alpha}{b_u c}$$

n_ℓ: number of lines
d_ℓ: diameter of a line
l: mean line length
$b_u c$: kite area
α: angle of incidence

Total lift coefficient

$$C_{Lk} = C_L + C_{Lc}$$

$$C_{Lc} = k_1 \sin^2(\alpha - \alpha_{ZL}) \cos(\alpha - \alpha_{ZL})$$

Total drag coefficient

$$C_{Dk} = C_{D0} + C_{iD} + \frac{n_\ell d_\ell l \cos^3 \alpha}{b_u c}$$

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Modelling: Aerodynamic Coefficients

- For the tether
  (following Hoerner 1965)

$$C_{Lt} = C_{D0} \sin\theta \cos^2\theta$$
$$C_{Dt} = C_{D0} \cos^3\theta + \Delta C_{D0}$$

d_t diameter of tether
l_t: length of tether
n_t: number of tethers
n_{cl}: number of control lines

$$C_{D0} = n_t C_{D0t} + n_{cl} C_{D0cl}$$
$$C_{D0} = 0.44(d_t / l_t) + 4C_f (l_t / d_t) + 4C_f (d_t / l_t)^{0.5}$$
$$\Delta C_{D0} = \pi C_f$$
$$C_f \approx 0.004$$

Modelling: Aerodynamic Coefficients

- Effective glide ratio
  (from Houska and Diehl, 2009)

$$G_e = \frac{C_{L_k}}{C_{D_k} + C_{Dt} d_t l_t / (4A_k)}$$

l_t: length of tether
d_t: diameter of tether
A_k: area of the kite

Modelling: Dynamic model

Very simple dynamic model

(following Goela et al., 1986)

$$(m_k + \mu_t l_t)\dot{v}^t = F_{Lk}\sin(\theta+\phi) + F_{Dk}\cos(\theta+\phi) + F_{Dt}\cos(\theta) - P_r / v^t$$
$$-F_{Lt}\sin(\theta) - (m_k + \mu_t l_t)\,g\sin(\theta) - (m_k + 0.5\mu_t l_t) v^{\perp 2} / l_t$$

$$(m_k + \mu_t l_t)\dot{v}^{\perp} = -F_{Lk}\cos(\theta+\phi) + F_{Dk}\sin(\theta+\phi)$$
$$+0.5F_{Dt}\sin(\theta) + 0.5F_{Lt}\cos(\theta)$$
$$+(m_k + 0.5\mu_t l_t)\,g\cos(\theta) + 2(m_k + \mu_t l_t / 3) v^{\perp} v^t / l_t$$

$$dl_t / dt = v^t$$
$$d\theta / dt = v^{\perp} / l_t$$

$$v_r^2 = v_w^2 + v_k^2 - 2 v_w v_k \cos\gamma$$

$$F_{Lk} = 0.5\rho_a A_k C_{Lk} v_r^2 \quad F_{Dk} = 0.5\rho_a A_k C_{Dk} v_r^2 \quad \gamma = \theta - \tan^{-1}(v^{\perp} / v^t)$$

$$F_{Lt} = 0.5\rho_a d_t l_t C_{Lt} v_w^2 \quad F_{Dt} = 0.5\rho_a d_t l_t C_{Dt} v_w^2 \quad v_k^2 = v^{t2} + v^{\perp 2}$$

Modelling: Dynamic model

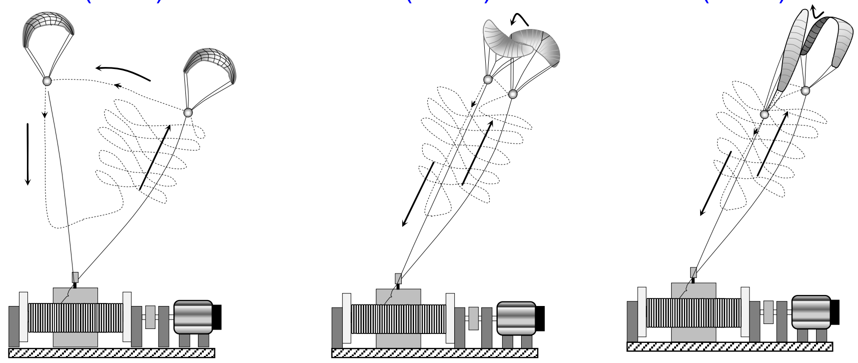
Steady-state model

$$F_{Dk}\cos(\theta+\phi) + F_{Lk}\sin(\theta+\phi) + F_{Dt}\cos(\theta) - P_r / v^t$$
$$-F_{Lt}\sin(\theta) - (m_k + \mu_t l_t)\,g\sin(\theta) - (m_k + 0.5\mu_t l_t) v^{\perp 2} / l_t = 0$$

$$F_{Dk}\sin(\theta+\phi) - F_{Lk}\cos(\theta+\phi) + 0.5F_{Dt}\sin(\theta) + 2(m_k + \mu_t l_t / 3) v^{\perp} v^t / l_t$$
$$+0.5F_{Lt}\cos(\theta) + (m_k + 0.5\mu_t l_t)\,g\cos(\theta) = 0$$

Approaches: Modelling Recovery Phase

Fly to Zenith (F2Z) | Pitch and Pull (P&P) | Free and Pull (F&P)



All kites | Rigid or semi rigid kites | Arc kites

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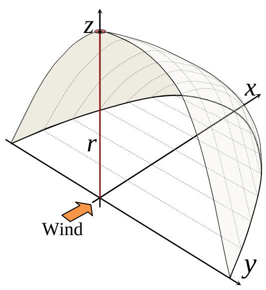
Approaches: Fly to Zenith

Option 1: $\theta = 0°, \varphi = 0° \Rightarrow \dot{\theta} = 0, \dot{\varphi} = 0$



$$F_r^{ae} = 0.5 \rho_a A_k \,(C_L G_e + C_D)\sqrt{1+G_e^2}\,(-v_k)^2$$

$$F_r^{aet} = 0.5 \rho_a d_t \, r \, C_f \,(-v_k)^2$$

$$F_r^{g} = (m_k + \mu_t \, r) g$$

$$F_r^{cf} = 0$$

$$C_{Lt} = 0 \quad C_{Dt} = C_{D0} + \Delta C_{D0} \approx 1.12$$

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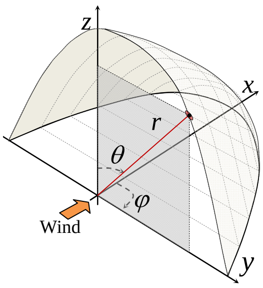
Approach: Fly to Zenith

Option 2: $\theta \neq 0°, \varphi = \pm 90° \Rightarrow \dot{\theta} = 0, \dot{\varphi} = 0$

$$F_r^{cf} = 0$$



$$F_r^{g} = (m_k + \mu_t\, r) g \cos\theta$$

$$v_{wr} = v_w \sin\theta \cos\varphi = 0$$

$$F_r^{ae} = 0.5 \rho_a A_k\, (C_L G_e + C_D) \sqrt{1 + G_e^2}\, (-v_k)^2$$

$$F_r^{aet} = 0.5 \rho_a d_t\, r\, C_f\, (-v_k)^2$$

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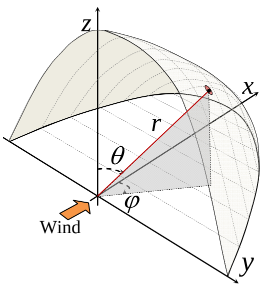
Approach: Flight Path
Approach: Fly to Zenith

Introduction | Modelling | Approaches | Approaches Models | Examples | Conclusions

$$\theta \neq 0°, \varphi \neq 0°$$

$$F_r^{ae} = 0.5 \rho_a A_k\, (C_L G_e + C_D) \sqrt{1 + G_e^2}\, (v_w - v_k)^2$$



$$F_r^{aet} = 0.5 \rho_a d_t\, r\, C_f\, (v_w - v_k)^2$$

$$F_r^{g} = (m_k + \mu_t\, r) g$$

$$F_r^{cf} = 0 \qquad v_{wr} = v_w \cos\theta \sin\varphi$$

$$C_{Lt} = 0 \qquad C_{D0} + \Delta C_{D0} \approx 1.12$$

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Approaches: Pitch and Roll Examples

Design examples (reference systems)

$t = 0.14\,c$ $\quad n_\ell = 1$ line per 1.1 m^2 $\quad A_p = 0$

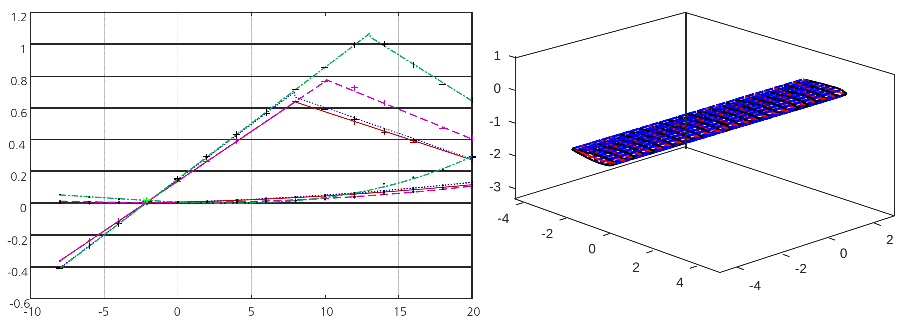
$l = 0.8 b_u$ $\quad a_0 = 6.89$ rad^{-1}

$d_\ell = 2.5$ mm $\quad \alpha_{ZL} = -7°$

Reference systems (Yo-Yo concept) (v_w = 10 m/s; h_m= 300 m; 3 tethers)				
Area of kite [m²]	15	18	213	2812
Aspect ratio	6.7	5	5	7
Number of cells	37	20	40	80
Span [m]	10.02	9.49	32.63	140.3
Cohr [m]	1.5	1.9	6.53	20.04
Mass [kg] (kite)	1.37	1.5	22	342
Density of mass [kg/m]	0.0883	0.0883	0.9654	6.5436
Diameter [mm]	4	4	12	39
Max. force [kN]	17	17	148	1475
Rated power [kW]	23	20	200	2000

Examples

Design examples (reference systems)



Examples

Design examples (reference systems)

Reference systems (Yo-Yo concept) (v_w = 10 m/s; h_{max}= 400 m; h_{min} = 200 m, 3 main tethers)				
20 kW				
Angle θ [°]	0	30	30	30
Angle φ [°]	0	45	60	90
Time [s]	24.83	39.38	37.32	1934.1
200 kW				
Angle θ [°]	0	30	30	30
Angle φ [°]	0	45	60	90
Time [s]	32.23	46.46	273.16	2991.1

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Conclusions

- The recovery phase is essential, it depends on the system dynamic and cannot be approximated as a percentage of the generation phase
- F2Z exploits the recovery outside the power zone and the positioning of the kite for zero lift
- The drawback is the time necessary for reaching the zenith plane
- P&P also utilises the positioning for zero lift
- The disadvantage: the recovery takes place in the power zone

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