A Wake Model for Crosswind Kite Systems

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1. Highlights

- The induction factor a and wake profile for two different kite systems were calculated computationally.
- The kite has a simplified straight downwind configuration.
- For a large-scale (~2MW) kite system: $a = 0.126$ (computationally), and $a = 0.14$ (analytically).
- For a small-scale (~100kW) kite system: $a = 0.046$ (computationally), and $a = 0.045$ (analytically).

3. Objectives

- The short-term objective is to study the wake characteristics of crosswind kite systems using CFD
- The long-term vision is to develop a semi-empirical wake model

2. Motivations

- To obtain the total harvested power for a given kite farm lay-out
- To find the optimal kite farm lay-out

4. Background & Theory

- General perception: the induction factor of a crosswind kite system is always negligible; e.g. Loyd [1] neglected "the induced effects of the kite slowing the wind."
- Following equations were proposed for kites in the straight downwind configuration [2]:

$$\frac{a}{1-a} \simeq \frac{1}{4}\left(\frac{A_k}{A_s}\right)C_L\left(\frac{C_L}{C_D}\right)^2$$

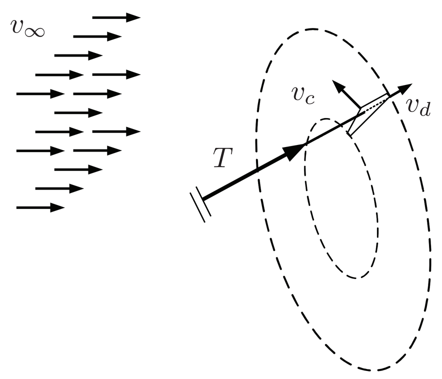

Figure 1: 'Lift' or ground-based generation mode

$$P_L = \left(\frac{1}{2}\rho A_k {v_\infty}^3\right) c_L\left(\frac{c_L}{c_D}\right)^2 (1-a)^2(1-e)^2 e$$

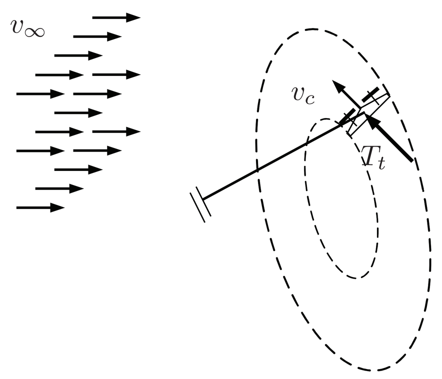

Figure 2: 'Drag' or on-board generation mode

$$P_D = \left(\frac{1}{2}\rho A_k {v_\infty}^3\right) c_L\left(\frac{c_L}{c_D}\right)^2 (1-a)^3 \frac{\kappa}{(1+\kappa)^3}$$

5. Methodology: CFD simulations

Table 1: CFD simulations setting

Platform	ANSYS R16.2
No. of processors	12
RAM	96 GB
Turbulence model	$k-\varepsilon$
Pres.-Vel. coupling	SIMPLE
Mesh motion	sliding mesh
Time step size	1 deg
For the Large-Scale Kite	
Mesh count	5.8 M
Total CPU time	25 days

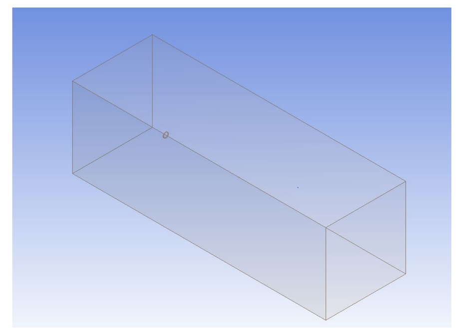

Figure 3: Solution domain

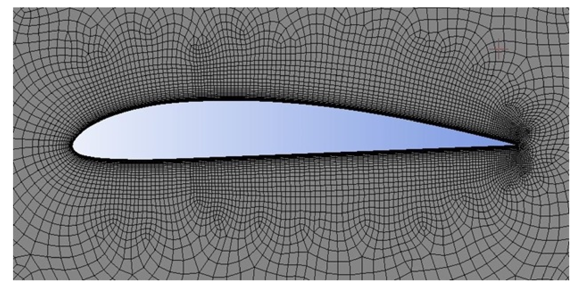

Figure 5: Mesh around the wing section

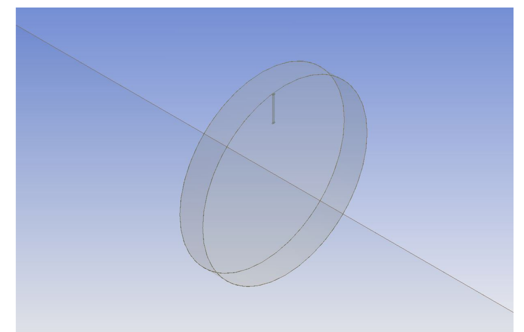

Figure 4: Close-up of the kite

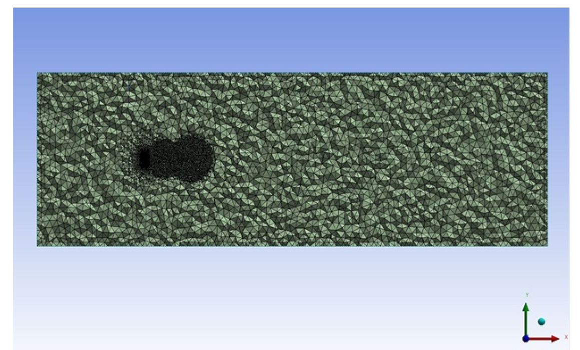

Figure 6: Solution domain mesh

6. Test Cases

Table 2: Small-scale kite system configuration

Power	~ 100 kW	R	79.9 m
Airfoil type	Clark-Y	A_s	8788 m^2
A_k (wing area)	23.5 m^2	v_∞	10.54 m/s
b (wing span)	17.5 m	v_c	80.31 m/s
AR	13	e	0

Table 3: Large-scale kite system configuration

Power	~ 2 MW	R	123.3 m
Airfoil type	Clark-Y	A_s	41785 m^2
A_k (wing area)	200.7 m^2	v_∞	11.66 m/s
b (wing span)	53.94 m	v_c	91.03 m/s
AR	14.5	e	1/3

7. Results: Induction factor & Wake of a small-scale kite

Figure 7: Flow-field after 20 cycles

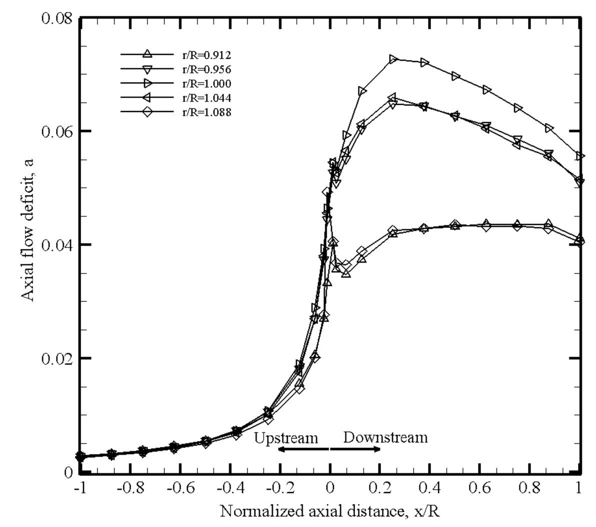

Figure 8: Flow deficit in the kite's vicinity. The average value at $x = 0$ is $a = 0.046$

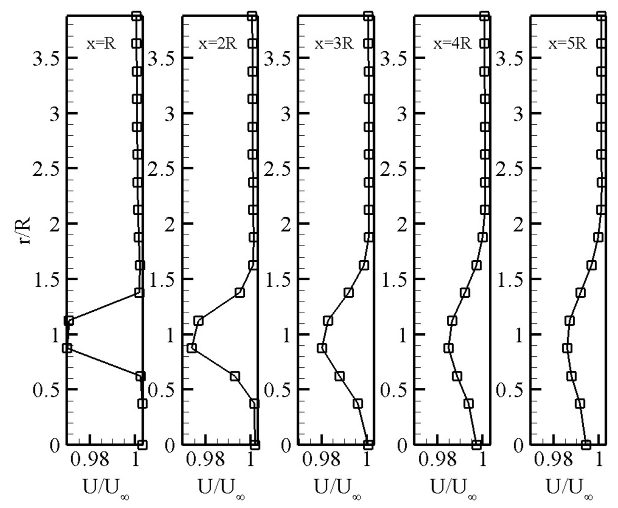

Figure 9: Wake profile at different x/R

8. Results: Induction factor & Wake of a large-scale kite

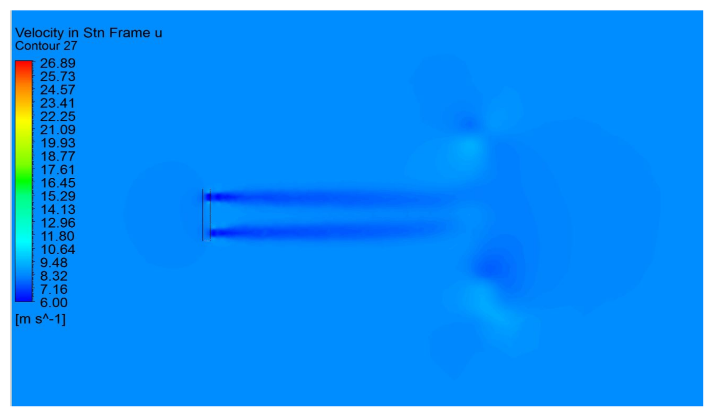

Figure 10: Flow-field after 27 cycles

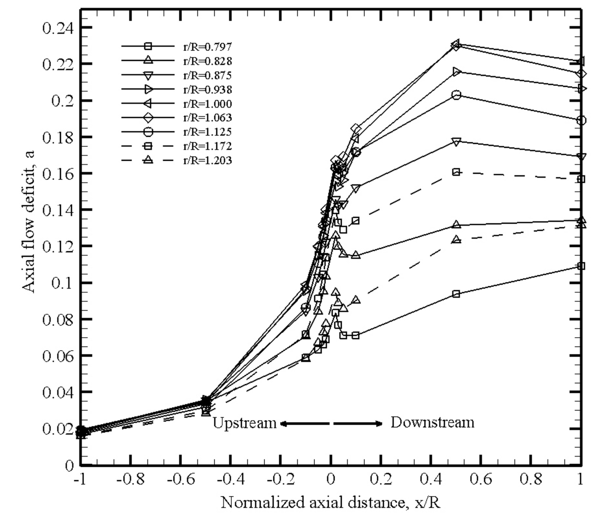

Figure 11: Flow deficit in the kite's vicinity. The average value at $x = 0$ is $a = 0.126$

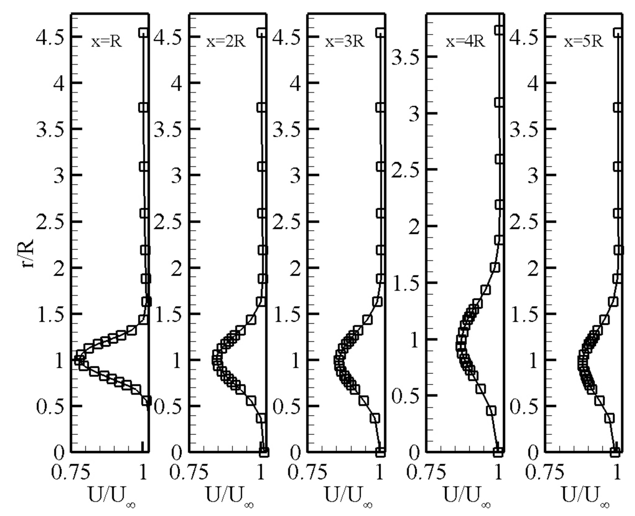

Figure 12: Wake profile at different x/R

9. Conclusions & Future work

- The induction factor, a, for a crosswind kite system may be significant; power may considerably be overestimated if a is neglected, e.g. 9% for the 100kW system and 24% for the 2MW system
- A noticeable low-speed wake flow is generated, which extends beyond the near-field region
- The actual inclined configuration, including the tether and wind gradient, will be modelled and solved computationally
- Attempt will be made to develop semi-empirical wake models
- Interactions between multiple kite systems will be studied computationally

Acknowledgement

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References

[1] Loyd, M.L., 1980. Crosswind kite power. *Journal of Energy (AIAA)*, 4(3), 106-111.

[2] Kheiri, M., Bourgault, F., and Saberi Nasrabad, V., 2017. Power limit for crosswind kite systems. In *Proc. of ISWTP 2017*, Montréal, Canada, 43-50.