Experimental Characterization of a Force-Controlled Flexible Wing Traction Kite

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In-flight flow measurement

We use an airborne sensor to capture inflow angles and apparent flow velocity v_a directly at the kite:

- No uncertainty from tether sag and unknown wind speed as for ground based measurements [1] [2]
- No limit in wing loading or kite size - the properties of any kite at relevant wing loading can be measured

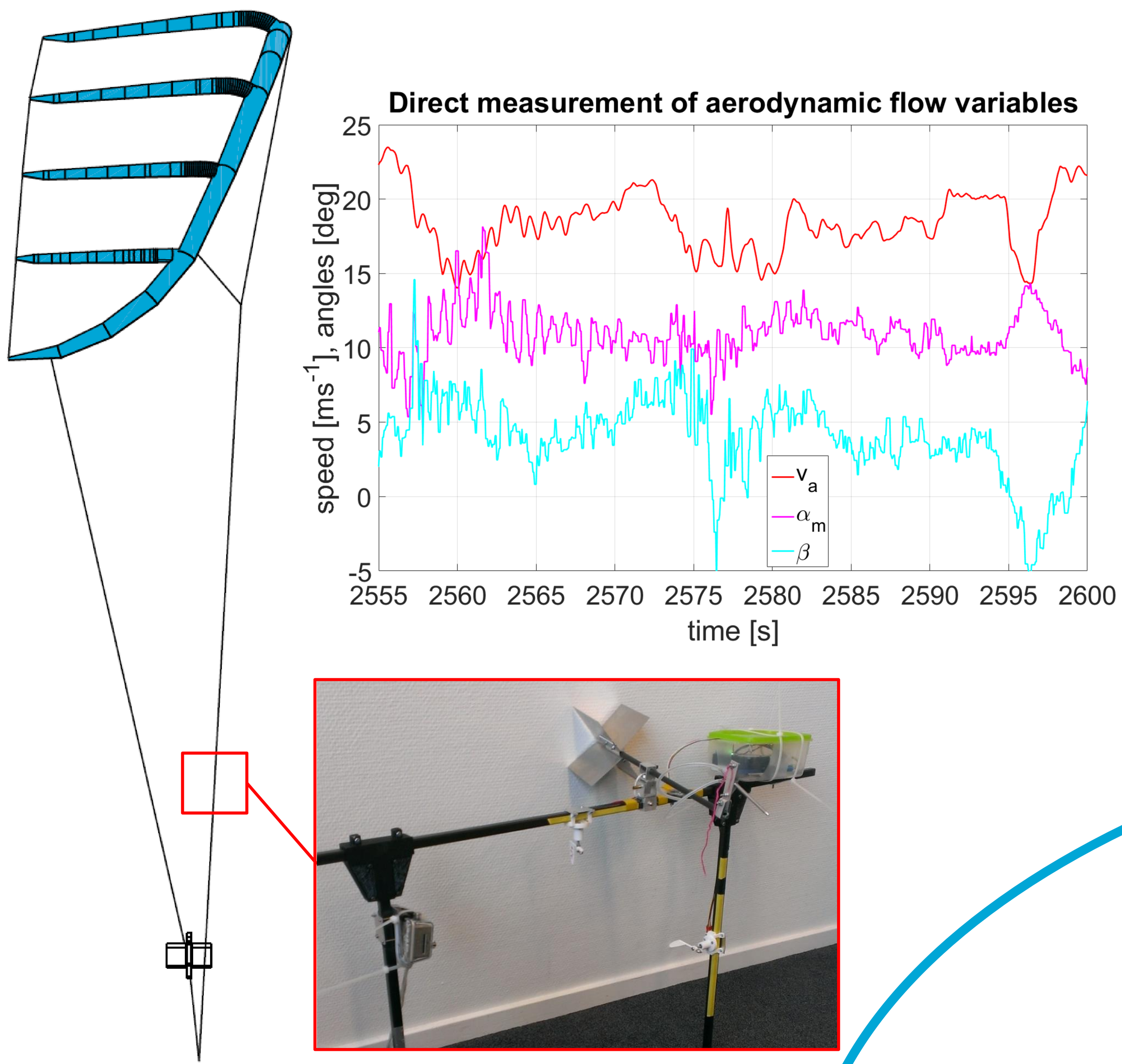


Fig. 1: Sensor position and recorded data of the air flow at the kite

Force control

When the kite operates at its predefined force limit, reeling velocity v_r is used to keep the tether force constant.

⇒ c_L and v_a can not vary independently

(1) $$L = \frac{\rho}{2} {v_a}^2 c_L S$$

Fig. 1 shows opposing trends for v_a and α_m:

⇒ High flow velocities must coincide with a low angle of attack to obey (Eq. 1)

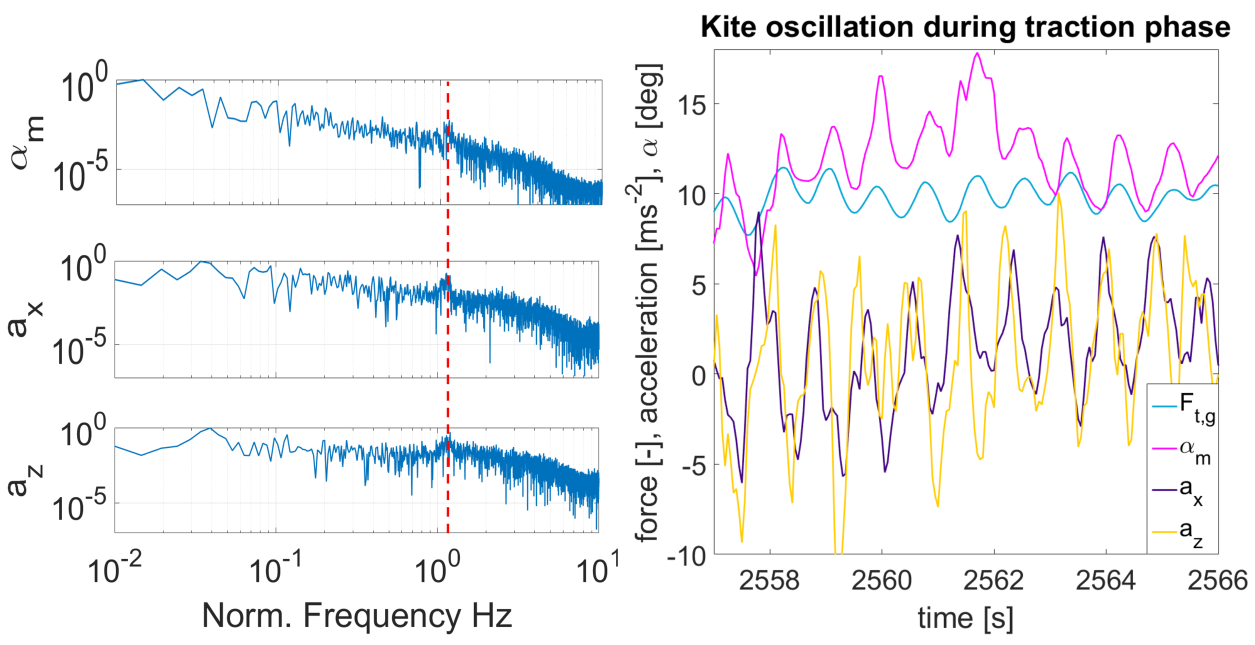


Fig. 2a: All variables show a peak at 1,2 Hz.

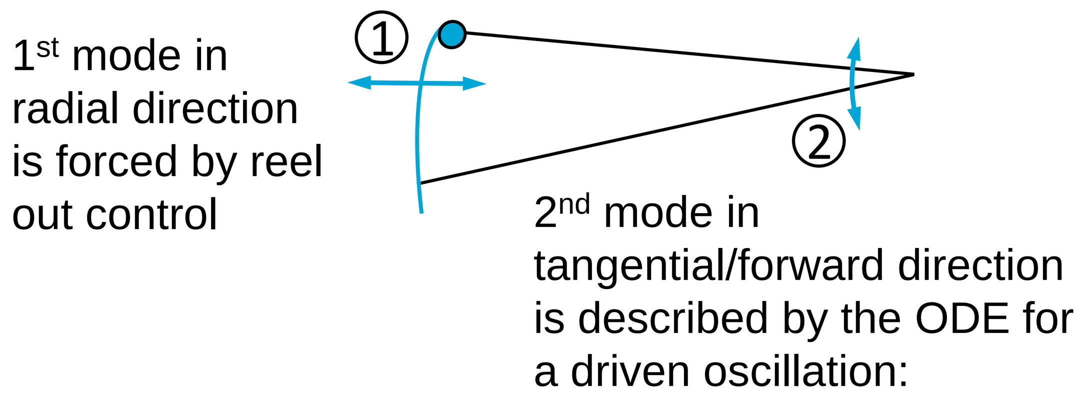
- *α_m shows a second maximum at the pumping cycle timescale of $T = 100\ s$.*
- *Accelerations peak at $T = 25\ s$ which is the timescale of one flight pattern (oval or eight).*

Fig. 2b: Maximum force occurs simultaneously with maxima in α_m. Both follow the maximum forward a_x and downward acceleration a_z with a delay of about $\frac{\pi}{2}$.

Oscillation of the kite

α_m, v_a (Flow)
v_r, F_t (Ground)
a_z, a_x (IMU)

Oscillate with $f = 1{,}2\ Hz$ for some flight situations



$$m\ddot{x} + \rho \overline{v_a} c_D S \dot{x} + F_a \frac{x}{B} = F(t) \qquad (2)$$

During traction phase we obtain:

$$f_0 = 0{,}81\ Hz \quad \& \quad \zeta = 0{,}63$$

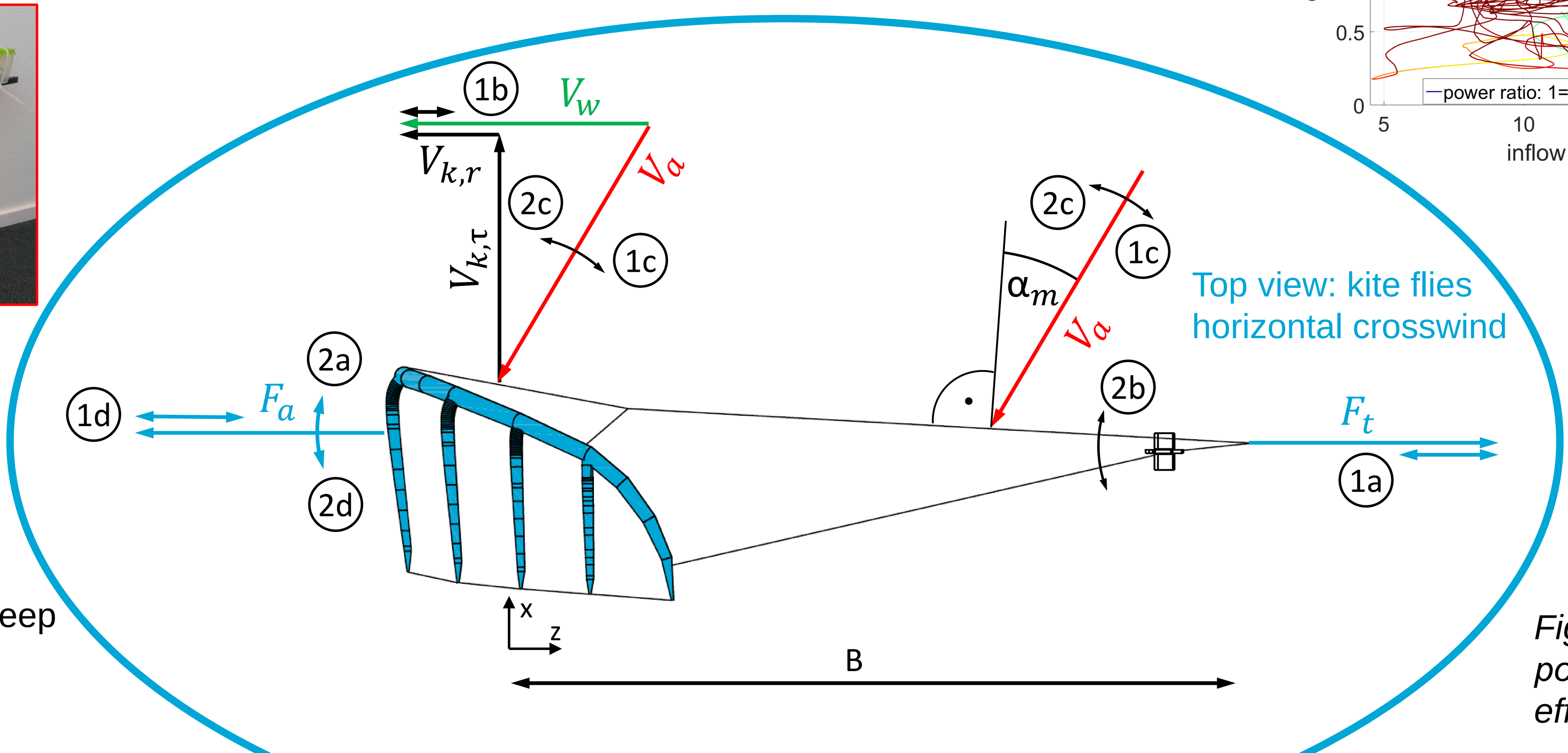


Fig. 3: Oscillation modes of the kite in traction phase

- Radial oscillation mode:
When tether force drops below intended value (1a):
v_r is reduced, $V_{k,r}$ (1b) drops and α_m (1c) enlarges.
⇒ F_a increases (1d) and overshoots intended value

- Tangential oscillation mode:
With α_m ↑: F_a tilts forward, kite accelerates (2a)
By moving forward (2b) kite pitches down by $\theta = \frac{x}{B}$,
α_m decreases (2c) and F_a tilts back again (2d).

Quasi-steady model

QSM [3] assumes that for kite manoeuvre timescale:

- Forces on the kite are balanced.
- Accelerations are negligible.

From fig. 2a: $T_{oscillation} \ll T_{manoeuvres}$

⇒ Shows the kite's quick reaction, backing QSM

⇒ QSM is used to calculate G and c_L from measured data

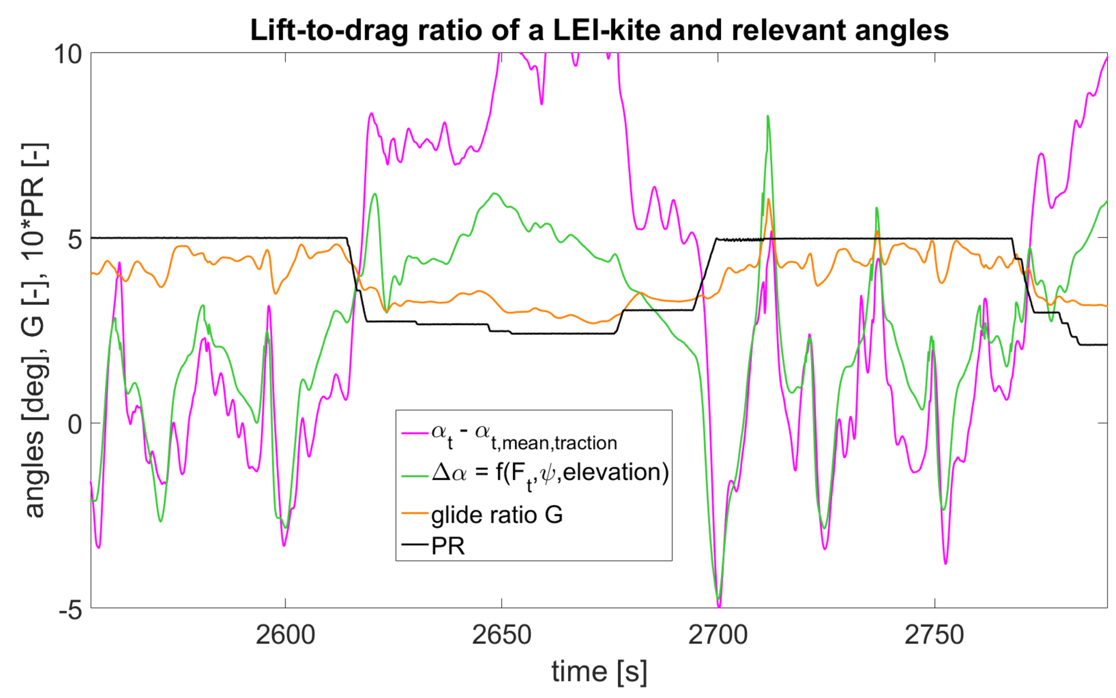


Fig. 4: When time averaged over 2,5 s measured α_t is equal to calculated $\Delta\alpha$ during traction phase.
⇒ Supports the assumption of quasi steady behaviour
G = 4,2 during traction phase; G = 3 during retraction.

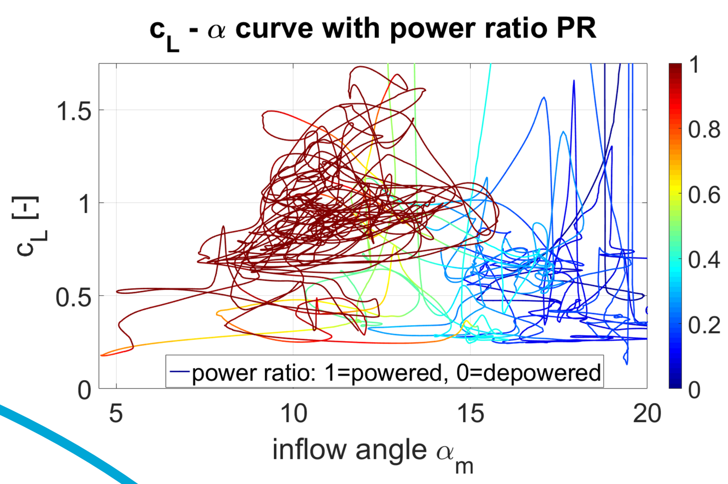


Fig. 5: $c_L - \alpha$ curve is dissimilar for powered and depowered flight.

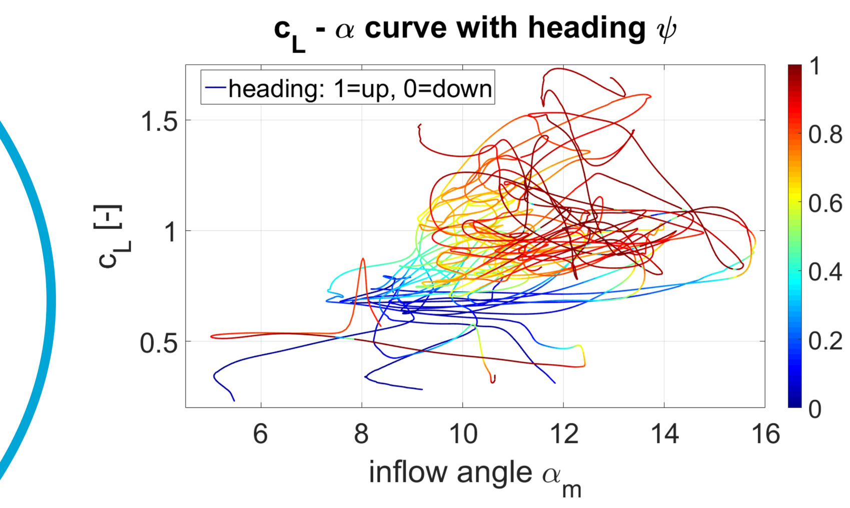


Fig. 6: During traction phase with constant power ratio the kite's heading has a big effect on angle of attack and thus c_L.

Conclusion

- Quasi-steady kite flight can be presumed for the time scale of kite manoeuvres.
- The entire kite can oscillate - Eigen frequencies and control laws must be chosen carefully.
- c_L varies with power ratio and angle of attack, a dependant variable in a force-controlled system.
- Through weight the heading of the kite has the biggest influence on c_L.

References

[1] Python, B.: Methodology Improvement for Performance Assessment of Pumping Kite Power Wing. MSc Thesis TU Delft, 2017

[2] Oehler, J.: Measuring Apparent Flow Vector on a Flexible Wing Kite. MSc Thesis TU Delft, 2017

[3] van der Vlugt, R., Bley, A.,Noom, M., Schmehl, R.: Quasi-Steady Model of a Pumping Kite Power System. submitted to Renew. Energy, arXiv:1705.04133 [cs.SY], 2017