Experimental Characterization of a Force-Controlled Flexible Wing Traction Kite

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.

![Image](image1.png)

**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.

\[ \Rightarrow \Delta c_a \text{ and } \Delta v_a \text{ cannot vary independently} \]

(1)

Fig. 1 shows opposing trends for \( v_a \) and \( \Delta c_a \):

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

![Image](image2.png)

**Fig. 2a:** All variables show a peak at 1.2 Hz.

- \( \Delta c_a \) shows a second maximum at the pumping cycle timescale of \( T = 130 s \).
- Accelerations peak at \( T = 25 s \) which is the timescale of one light pattern (oval or eight).

![Image](image3.png)

**Fig. 2b:** Maximum force occurs simultaneously with maxima in \( \Delta c_a \). Both follow the maximum forward \( a_f \) and downward acceleration \( a_d \) with a delay of about \( \frac{T}{2} \).

Oscillation of the kite

\[ a_m \text{-} v_a \text{ (Flow)} \]
\[ v_r \text{-} F_r \text{ (Ground)} \]
\[ a_r \text{, } a_s \text{ (IMU)} \]

1st mode in radial direction is forced by reel out control

2nd mode in tangential/forward direction is described by the ODE for a driven oscillation:

\[ m \ddot{x} + p \varepsilon c_a S \dot{x} + F_x = F(t) \]

During traction phase we obtain:

\[ f_0 = 0.81 \text{ Hz} \quad \& \quad \zeta = 0.63 \]

![Image](image4.png)

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

- Radial oscillation mode:
  - When tether force drops below intended value \( \Rightarrow F_r \text{ increases } \) and overshoots intended value
  - Tangential oscillation mode:
    - With \( a_m \rightarrow F_x \text{ tilts forward, kite accelerated} \)
    - By moving forward \( \text{kite accelerates and } a_m \text{ decreases and } F_x \text{ tilts back again} \)

![Image](image5.png)

**Fig. 4:** When time averaged over 2.5 s measured \( c_a \) 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.

![Image](image6.png)

**Fig. 5:** \( c_a \) - a curve is dissimilar for powered and depowered flight.

Quasi-steady model

QSM \([3]\) assumes that for kite manoeuvre timescale:

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

From fig. 2a:

\[ T_{\text{oscillation}} \ll T_{\text{manoeuvre}} \]

\( \Rightarrow \) Shows the kite’s quick reaction, backing QSM

QSM is used to calculate \( G \) and \( c_a \) from measured data

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.
- \( c_a \) 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 \( c_a \).

References