



Airborne Wind Energy

Basic mechanics of crosswind kites I

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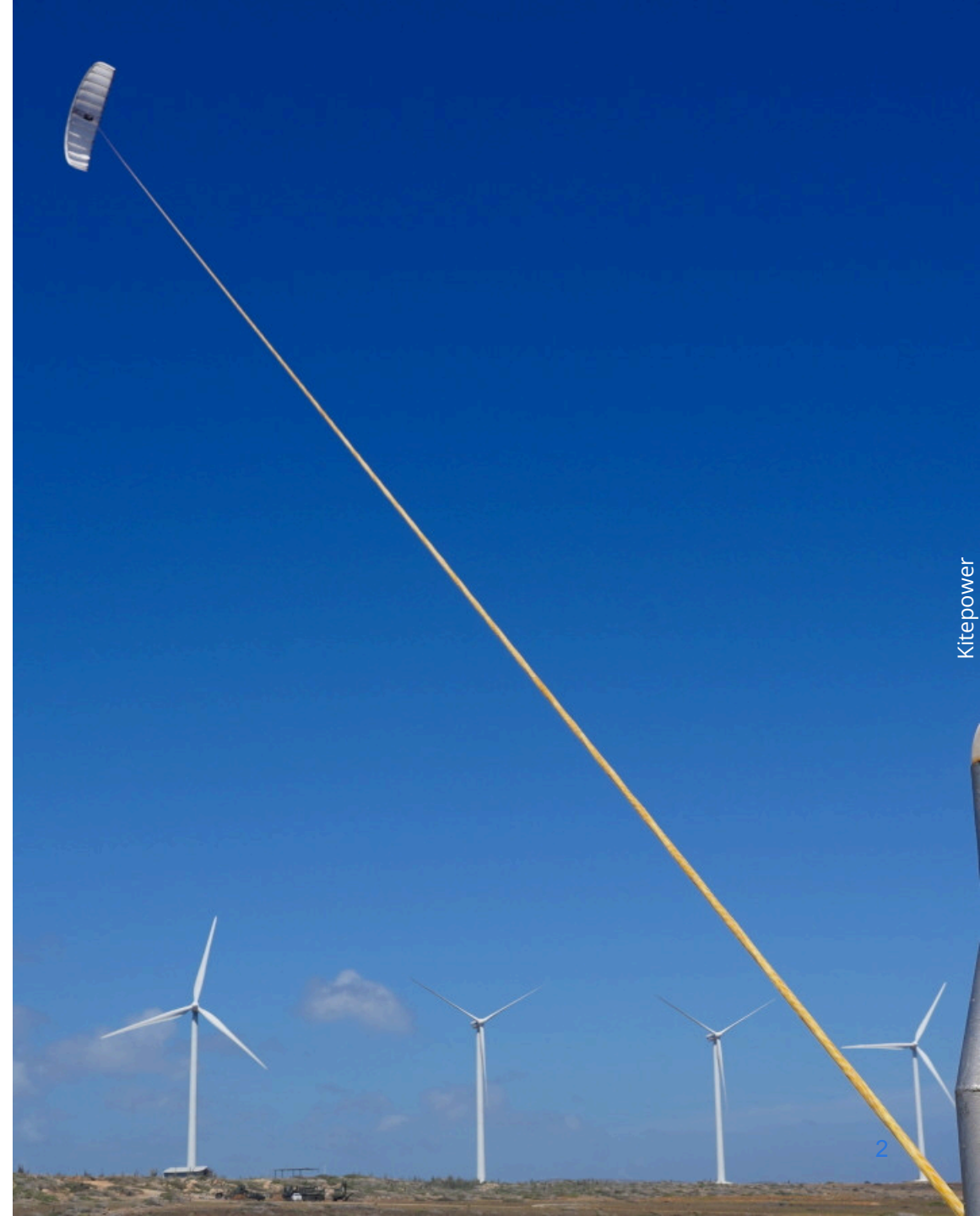
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Outlines

- Definitions and assumptions
- Kite kinematics
- Kite aerodynamics
- Steady gliding flight
- Tethered static flight
- Static take-off limit



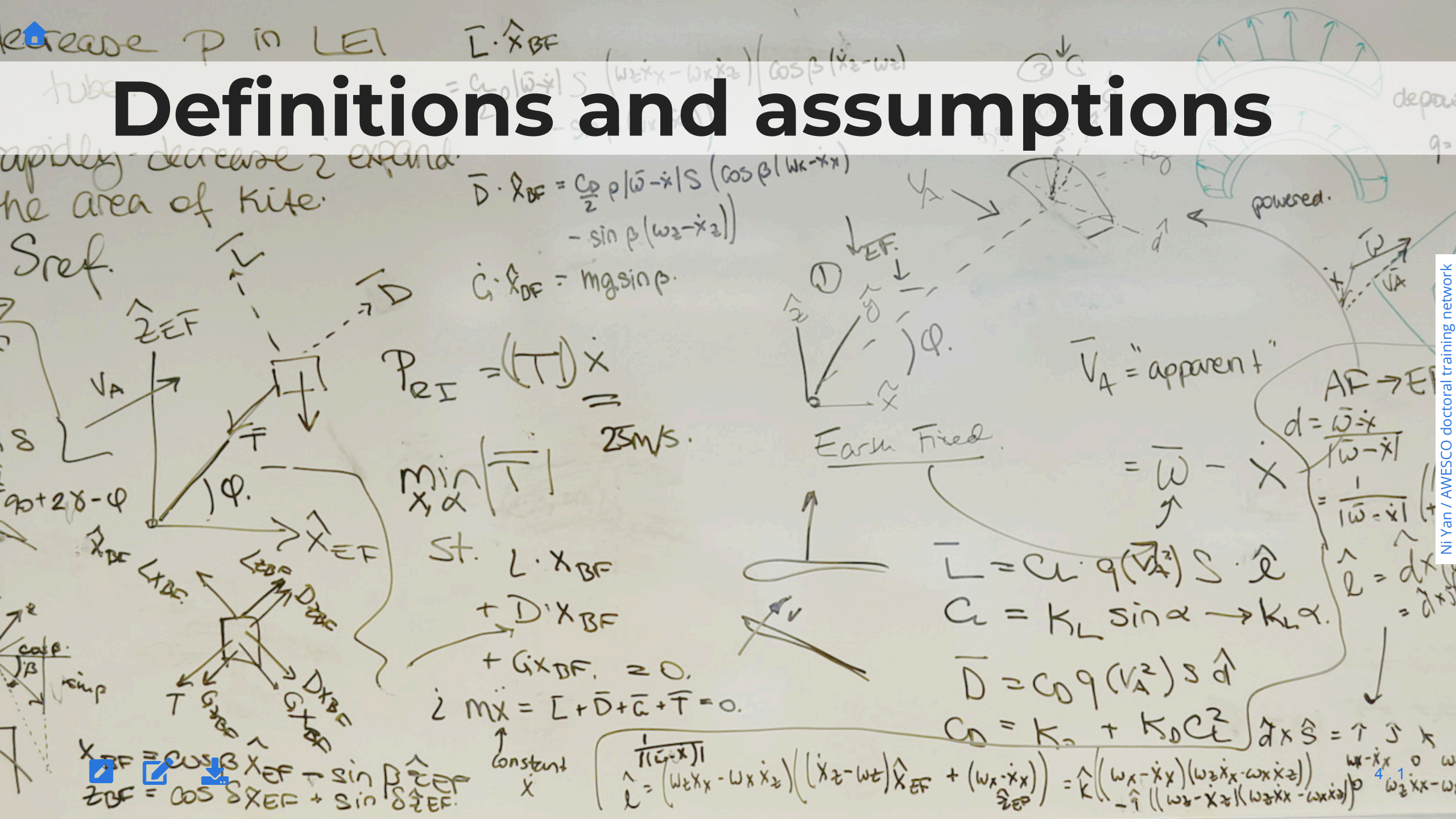


Learning objectives

- Derive a **basic theory** of tethered flight and energy harvesting with kites
- Identify all relevant **problem parameters**
- Introduce a consistent set of **non-dimensional numbers**
- Analyze **steady gliding** and **tethered static flight**
- Derive the **static take-off wind speed**

Relevant literature sources are Loyd ([1980](#)) and Diehl ([2013](#)).

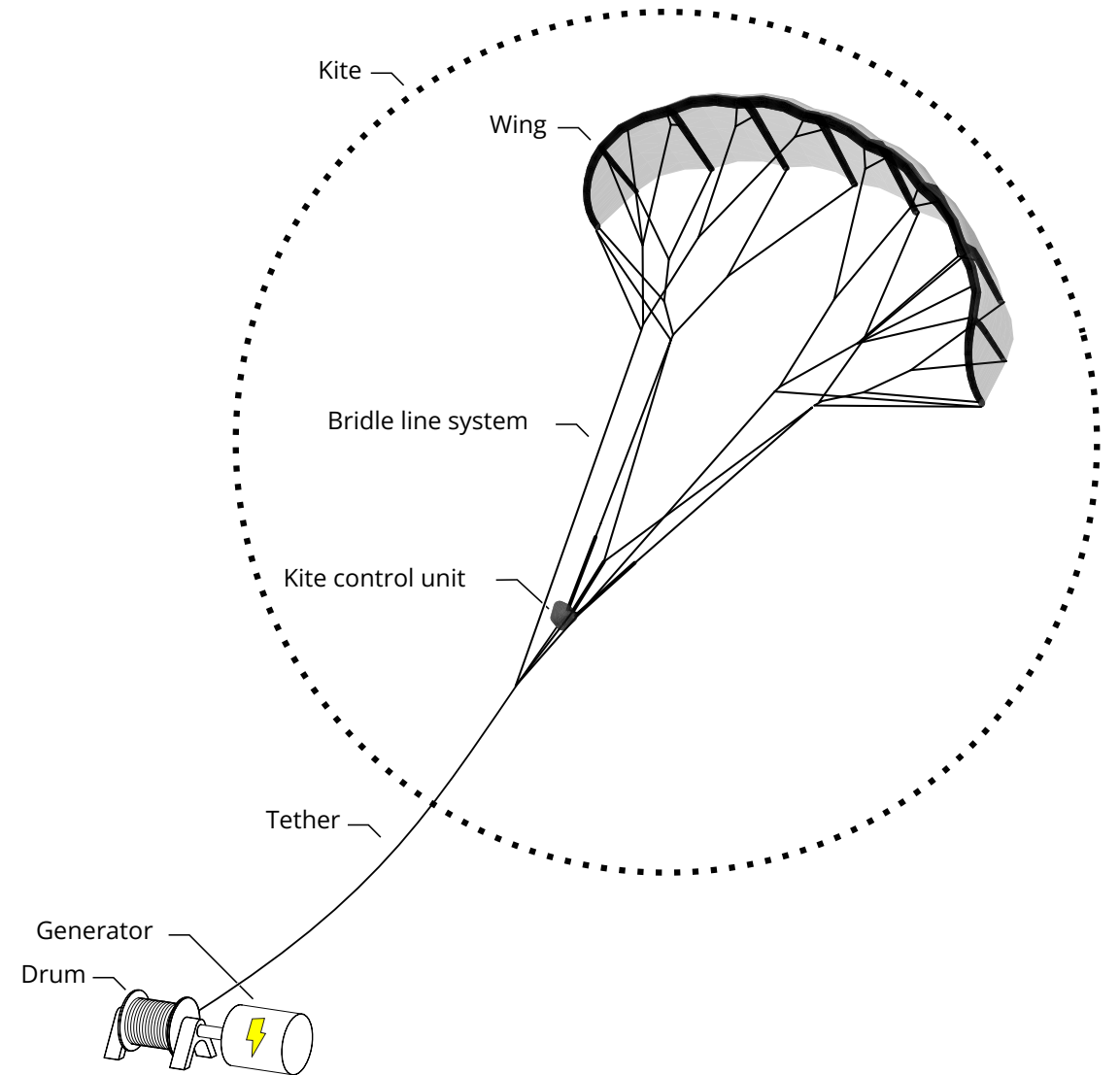
Definitions and assumptions





Terminology

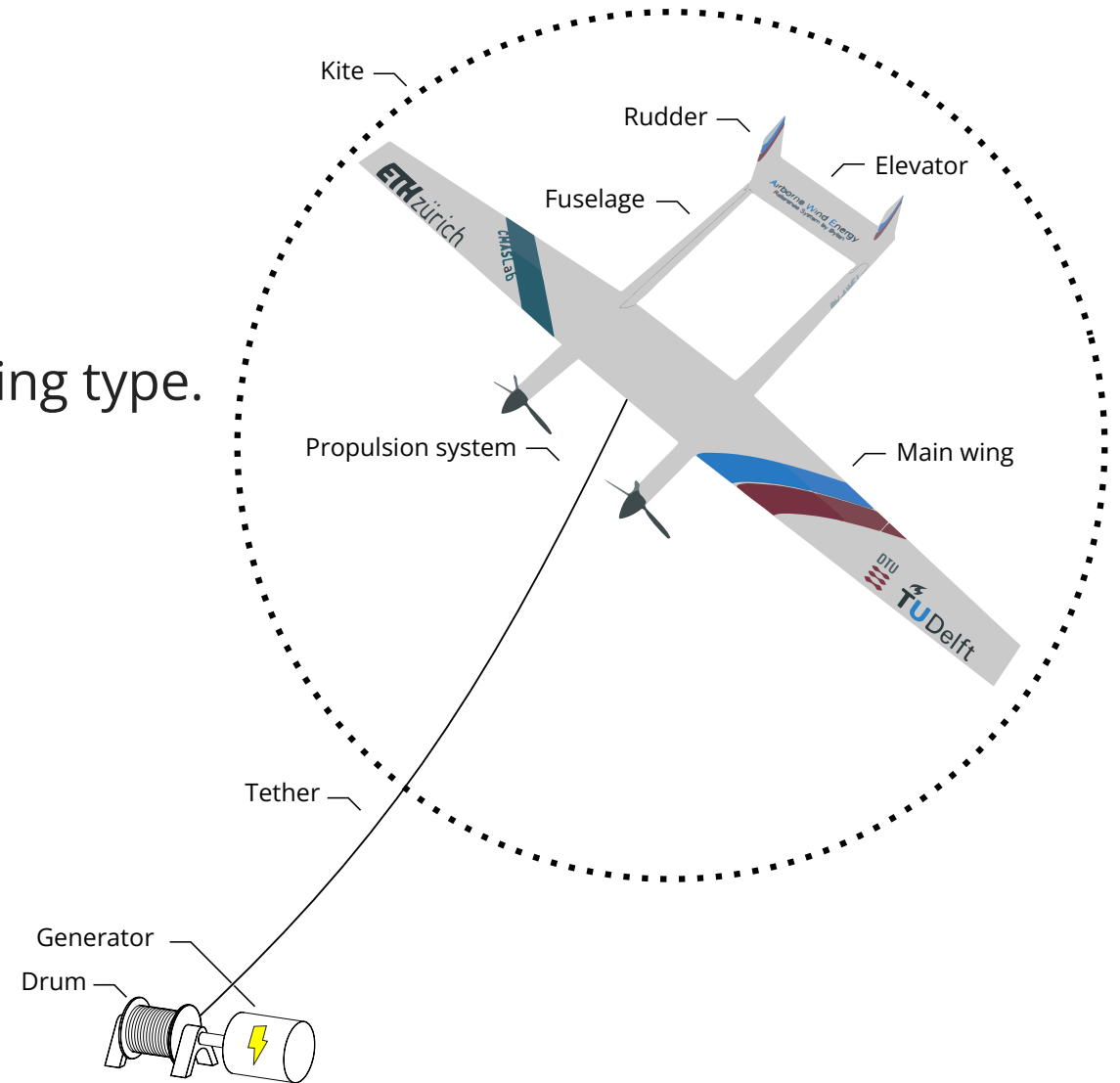
- Velocity is a vector property.
- Speed is a scalar property, the magnitude of the velocity vector.
- A kite can be of soft-wing type





Terminology

- Velocity is a vector property.
- Speed is a scalar property, the magnitude of the velocity vector.
- A kite can be of soft-wing type or of fixed-wing type.





Mathematical notation

- Scalars are set in italic: a, b, ρ, ϕ
- In digital resources, vectors are set in bold roman: $\mathbf{v}, \mathbf{L}, \mathbf{D}$
- In handwritten resources, vectors are overset with an arrow: $\vec{v}, \vec{L}, \vec{D}$
- Units are set in roman: m, kg
- Mathematical functions are set in roman: $\sin, \cos, \max$
- Product of scalars: ab
- Scalar product of vectors: $\mathbf{v} \cdot \mathbf{v} = v^2$
- Cross product of vectors: $\mathbf{v} = \boldsymbol{\omega} \times \mathbf{r}$
- Cartesian unit vectors: $\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z$



Environmental properties

Ambient wind velocity (vector field)

$$\mathbf{v}_w, \quad \text{m/s}$$

Air density (scalar field)

$$\rho, \quad \text{kg/m}^3$$

Dynamic wind pressure

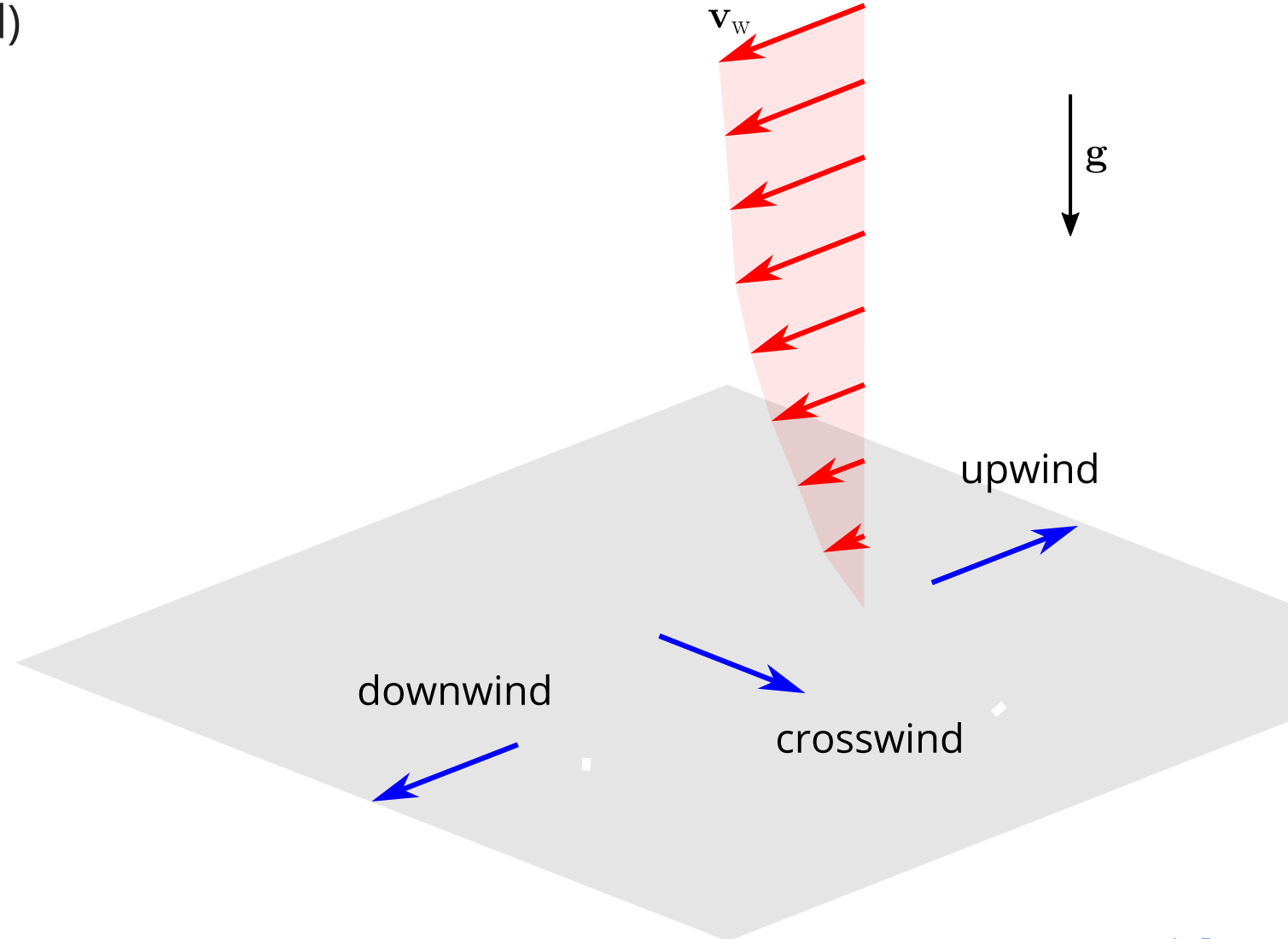
$$q = \frac{1}{2} \rho v_w^2, \quad \text{N/m}^2$$

Wind power density

$$P_w = \frac{1}{2} \rho v_w^3, \quad \text{W/m}^2$$

Gravitational acceleration

$$g, \quad \text{m/s}^2$$

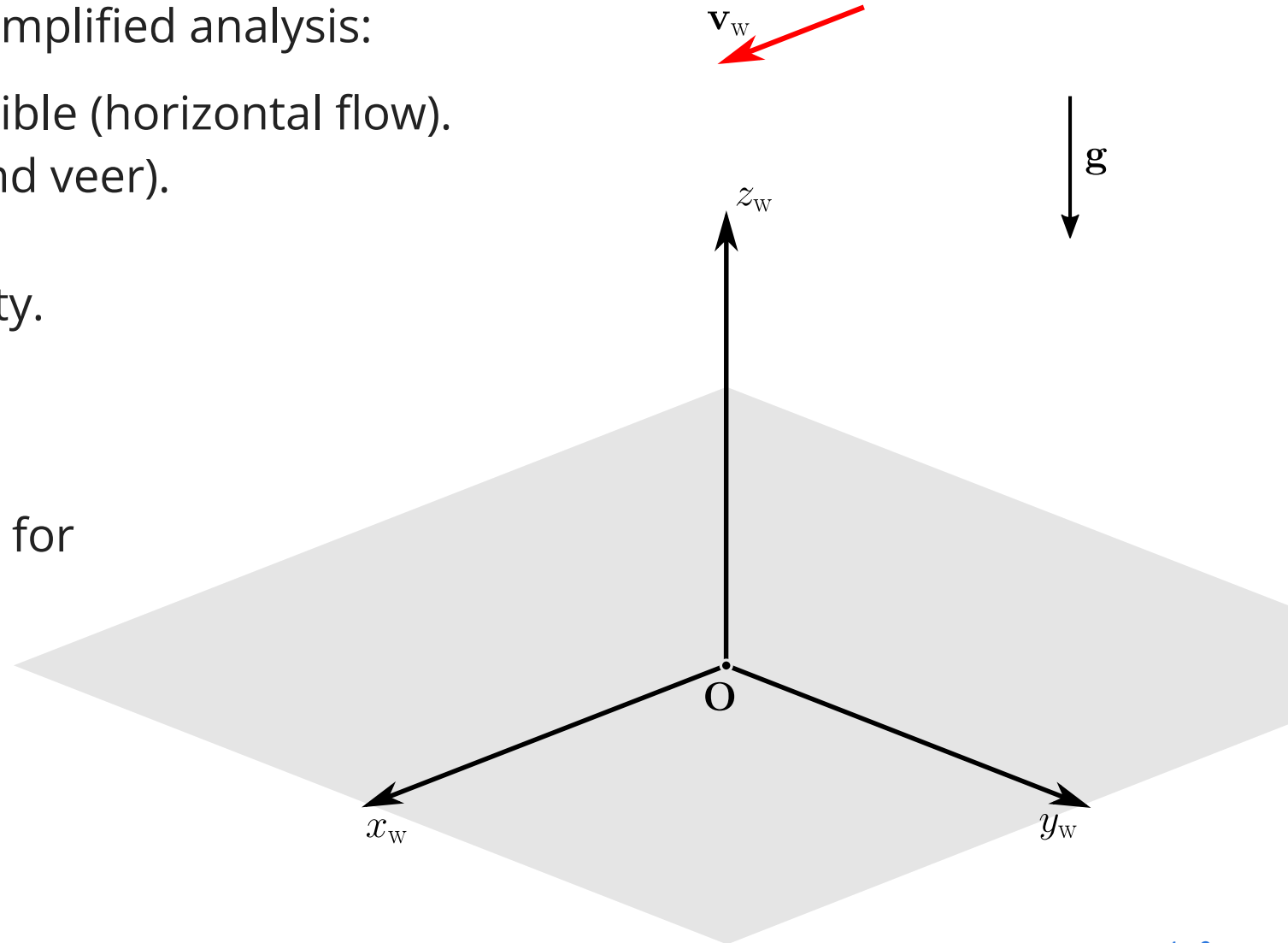




Wind reference frame

Reference frame (x_w, y_w, z_w) for simplified analysis:

- Vertical component of $\mathbf{v}_w$ negligible (horizontal flow).
 - Rotation of $\mathbf{v}_w$ negligible (no wind veer).
 - $\mathbf{v}_w$ uniform and constant.
 - x_w -axis aligned with wind velocity.
 - z_w -axis vertical upwards.
-
- These conditions will be relaxed for simulations of more complex, practical scenarios.





Kite properties

Flat wing surface area (unrolled)

Wing planform area (projected)

$S, \text{ m}^2$

Wing span

$b, \text{ m}$

Wing side area (projected)

Wing maximum chord

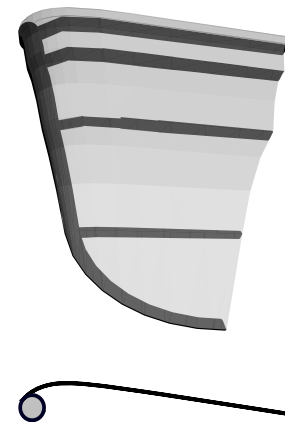
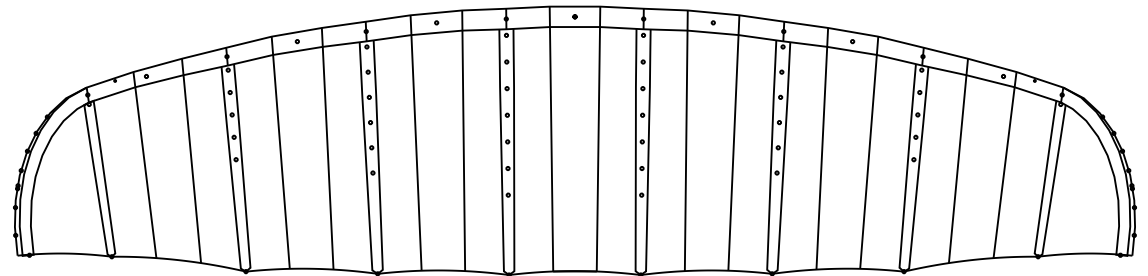
$c_{\text{max}}, \text{ m}$

Airfoil geometry

Kite mass¹

$m_k, \text{ kg}$

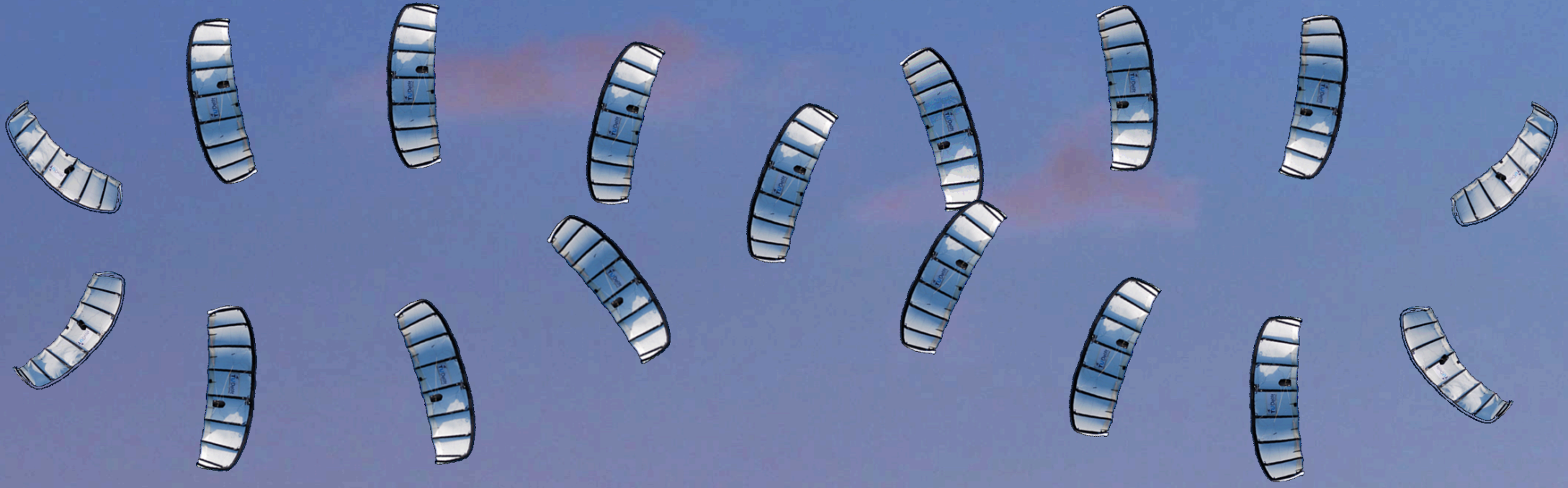
¹ Often also just denoted as m , without subscript.



Example: TU Delft V3 kite



Kite kinematics





Kite kinematics

Kite velocity

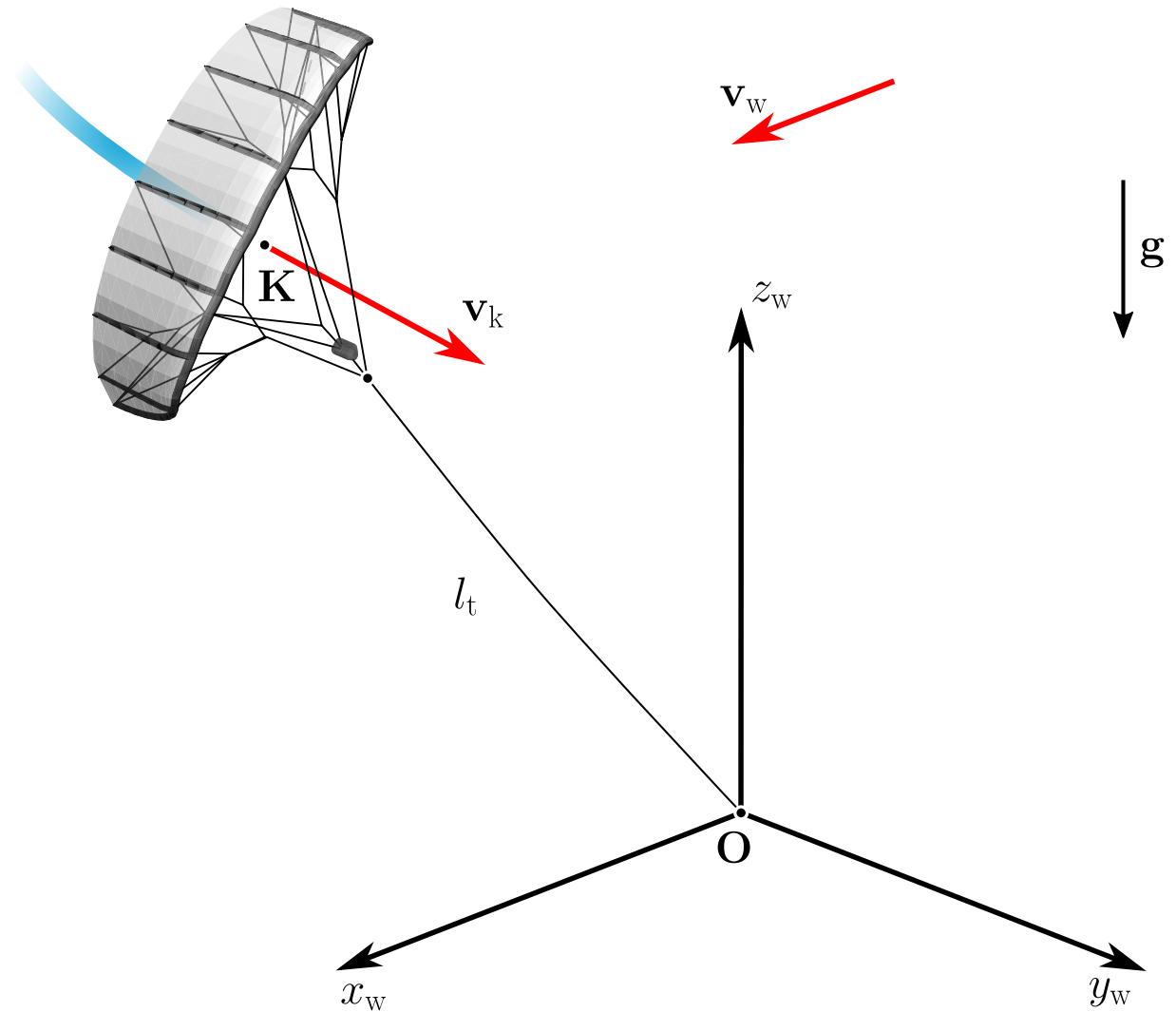
$$\mathbf{v}_k$$

Apparent wind velocity

$$\mathbf{v}_a = \mathbf{v}_w - \mathbf{v}_k$$

Resultant aerodynamic force

$$F_a = \frac{1}{2} \rho C_R S v_a^2, \quad \text{with} \quad v_a^2 = \mathbf{v}_a \cdot \mathbf{v}_a$$

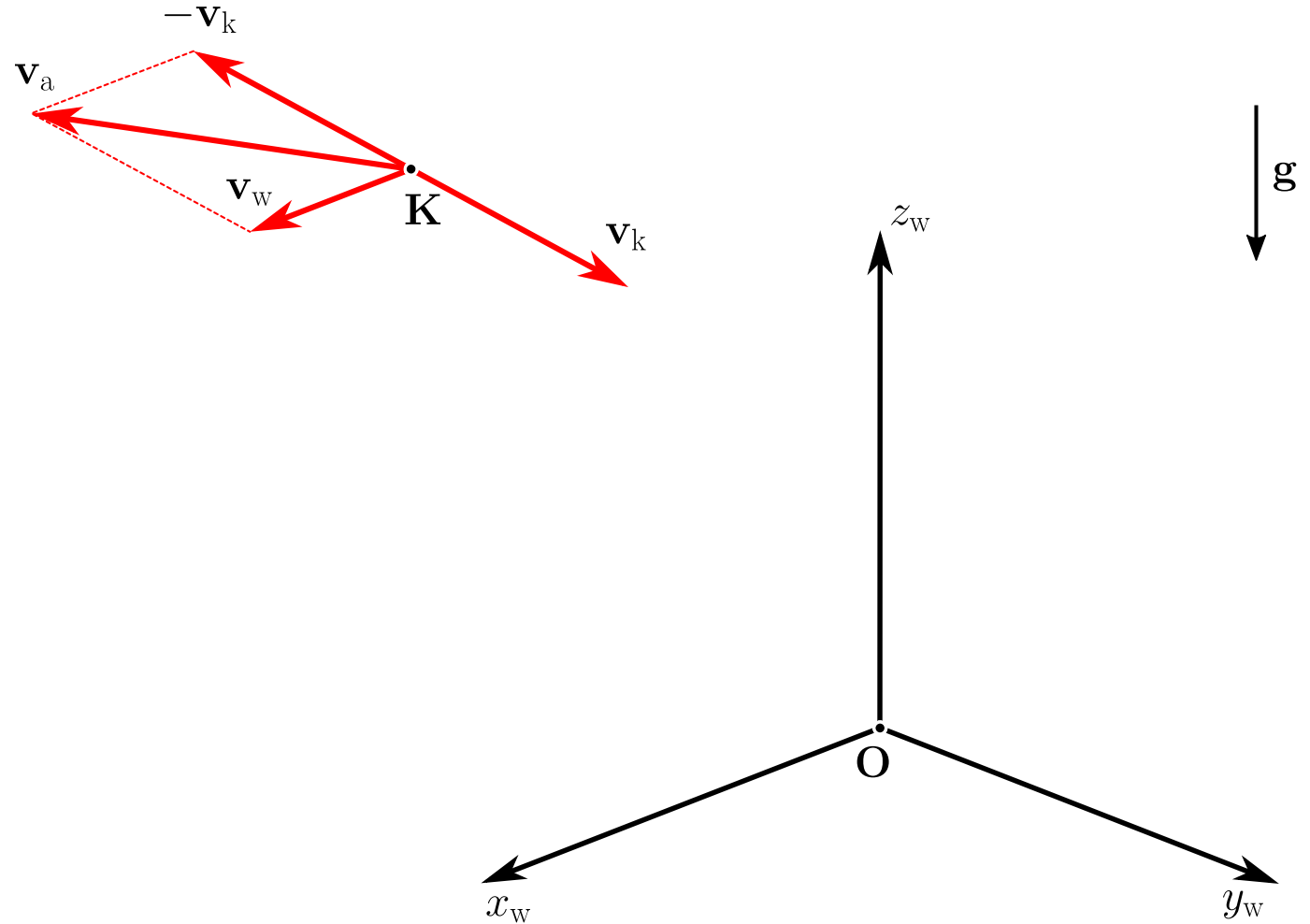




Apparent wind velocity

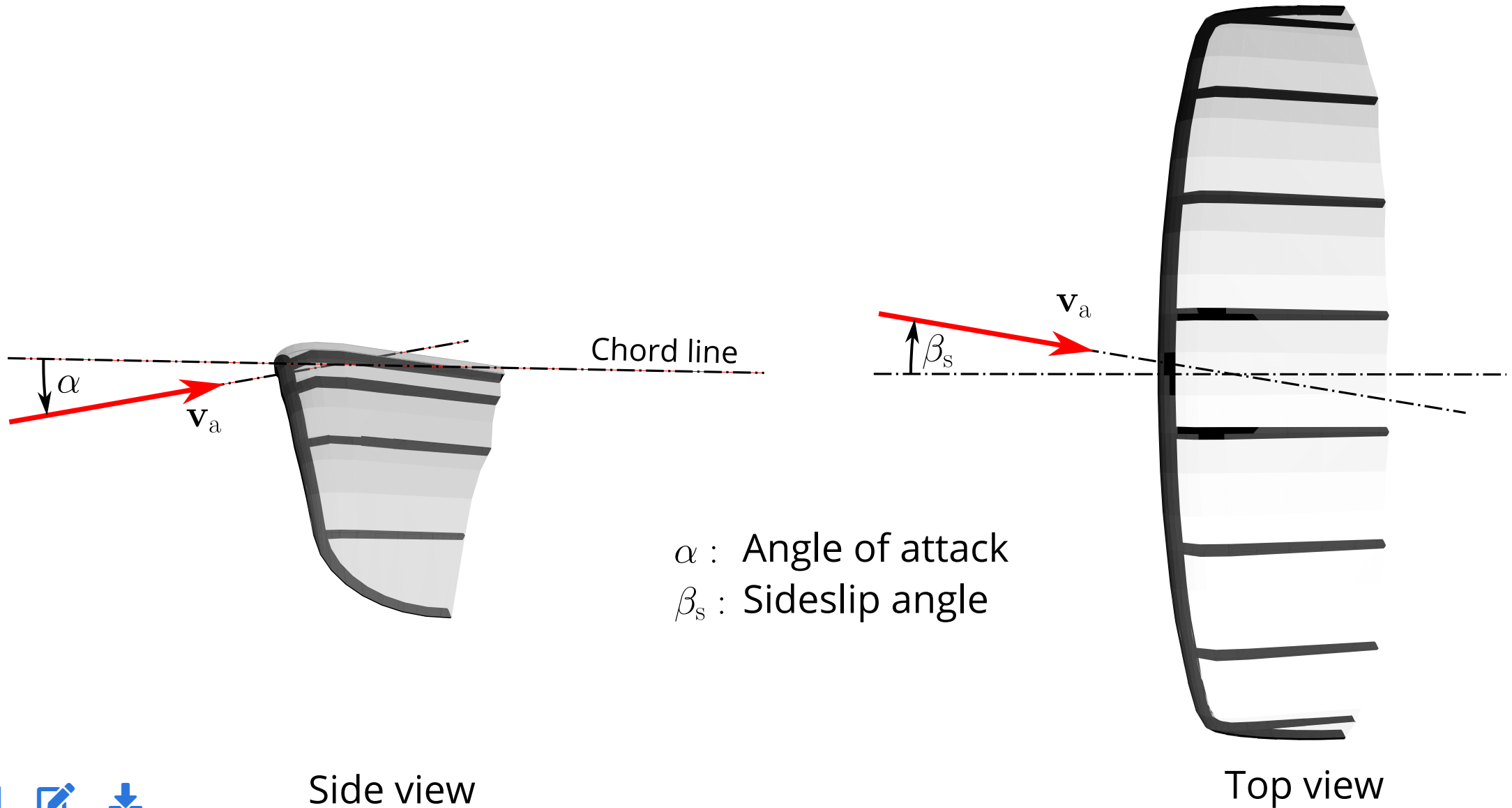
Apparent wind velocity

$$\mathbf{v}_a = \mathbf{v}_w - \mathbf{v}_k = \mathbf{v}_w + (-\mathbf{v}_k)$$



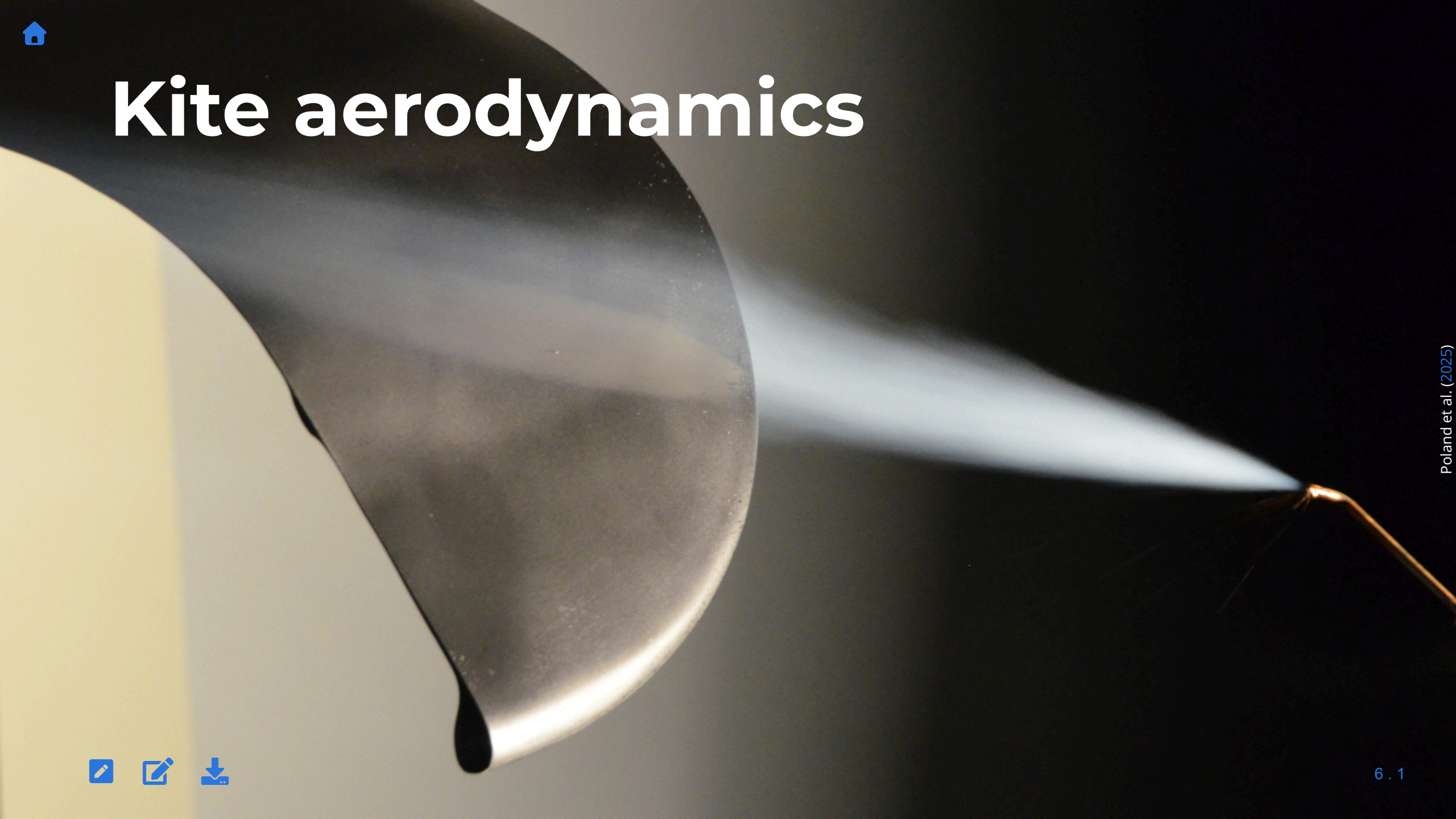


Relative flow





Kite aerodynamics

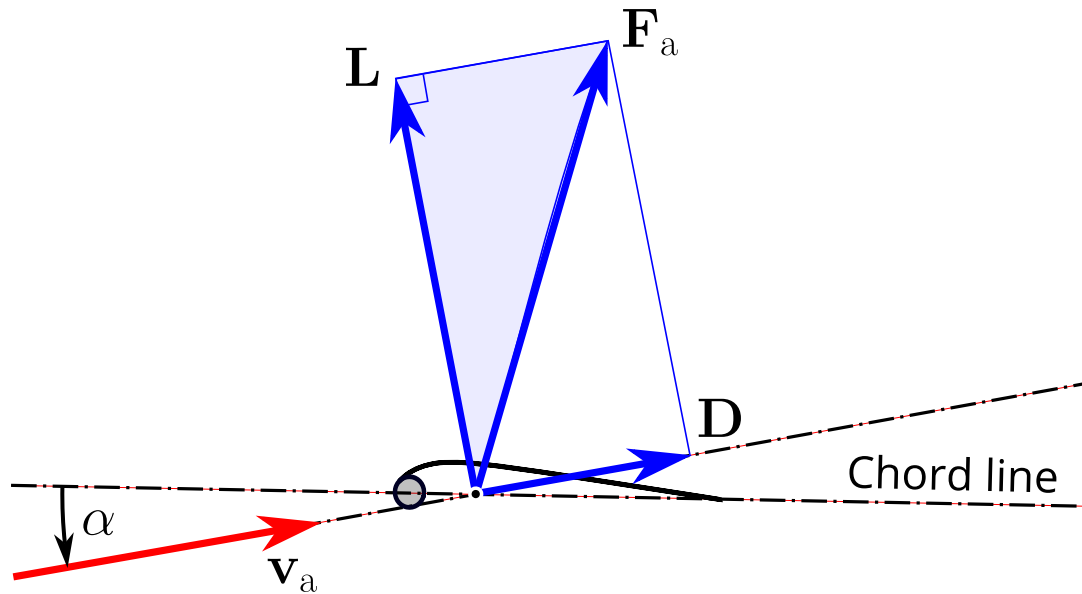


Poland et al. (2025)





Aerodynamic forces



Resultant aerodynamic force can be decomposed into lift and drag force

$$\mathbf{F}_a = \mathbf{L} + \mathbf{D}$$

Drag force component is defined as

$$\mathbf{D} \parallel \mathbf{v}_a$$

Lift force component is defined as

$$\mathbf{L} \perp \mathbf{v}_a$$

Aerodynamic side force $\mathbf{F}_{a,s} \sim \beta_s$
neglected for performance modeling.

$$\mathbf{L} = \frac{1}{2} \rho C_L S v_a^2$$

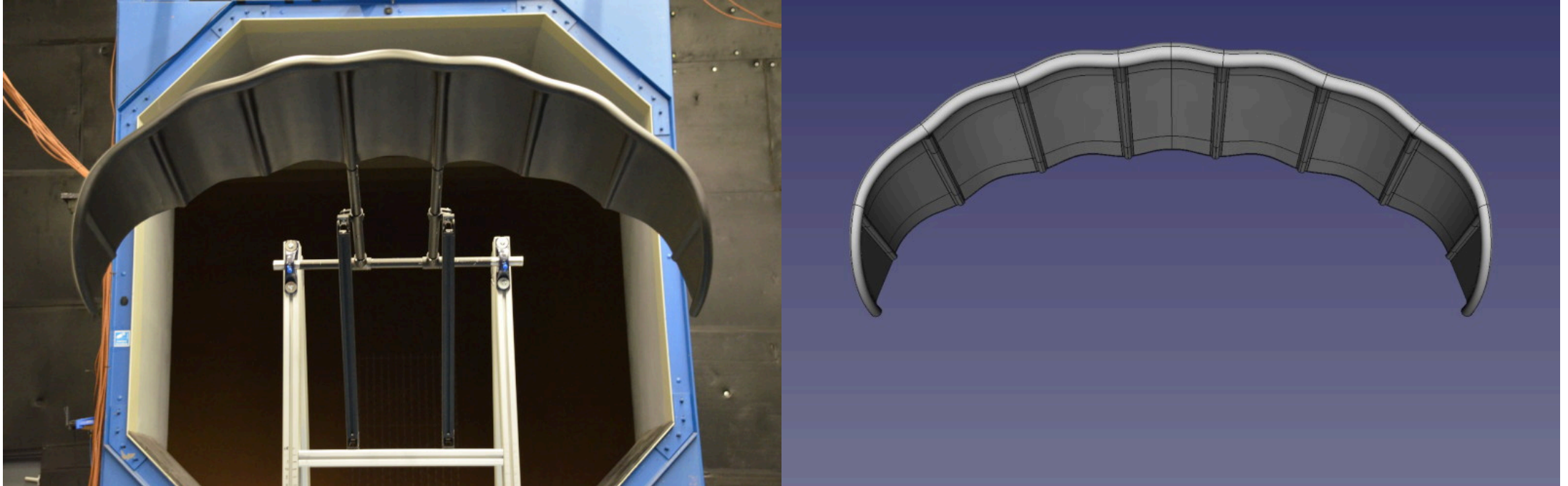
$$\mathbf{D} = \frac{1}{2} \rho C_D S v_a^2$$

Side view





Determining aerodynamic coefficients



Wind tunnel measurement

- Rigid scale model with 1.28 m span
- Unloaded design shape
- Variable angle of attack & side slip angle
- Reynolds number lower than real kite

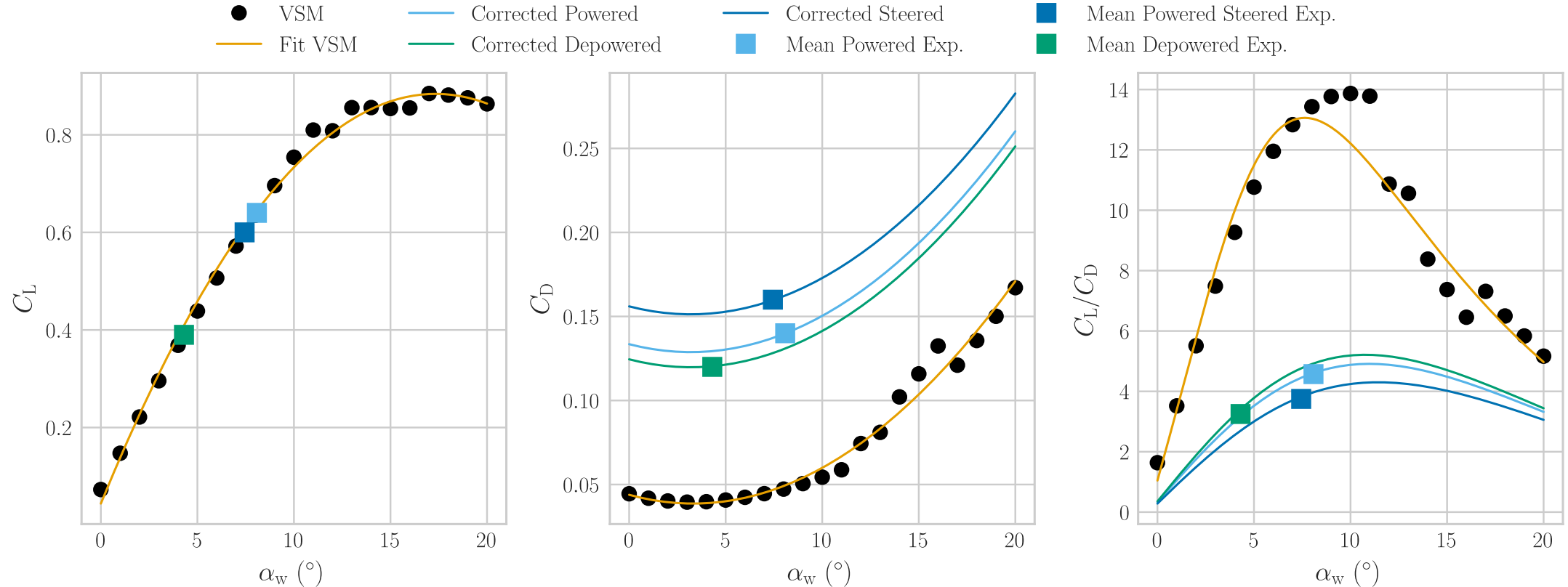


Computational Fluid Dynamics

- CAD model before meshing
- Unloaded design shape
- Variable angle of attack & side slip angle
- Uncertainty about captured physics



Aerodynamic characteristics



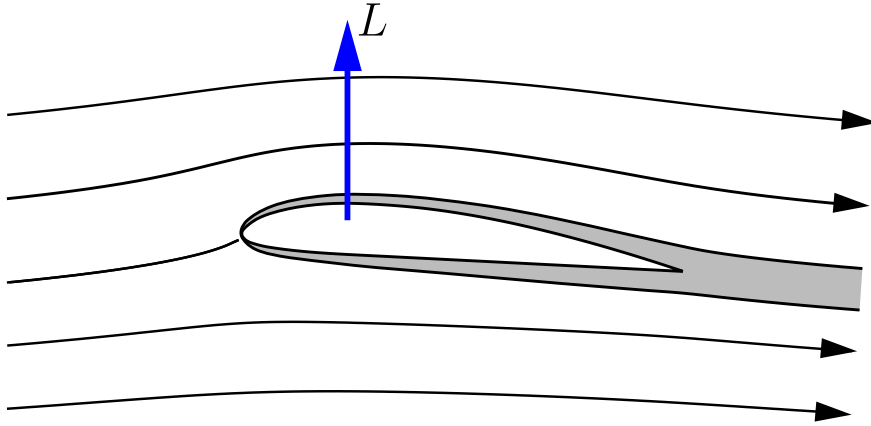
- Data for TU Delft V3 kite with empirical corrections for different flight phases: powered, depowered, steered.

Source: Cayon et al. (2025), with Vortex Step Method (VSM) as implemented in Cayon et al. (2023).



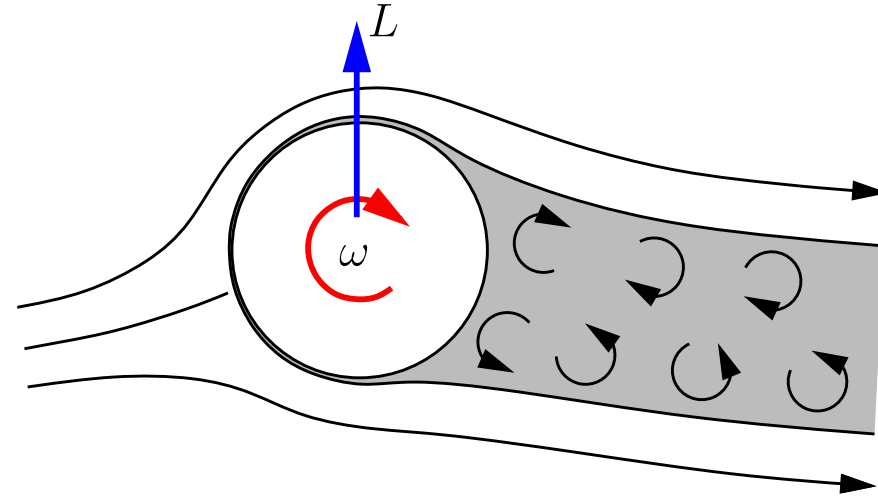


Aerodynamic lift devices



Airfoil

- Full range of L/D
- D can be minimised
- Control by angle of attack



Rotating cylinder

- Limited L/D
- D can not be modified
- Control by angular velocity



Steady gliding flight





Stagnant wind

Kite velocity

$$\mathbf{v}_k = \mathbf{v}_{k,x} + \mathbf{v}_{k,z} = \text{const.}$$

Glide ratio

$$E = \frac{v_{k,x}}{v_{k,z}} = \frac{1}{\tan \gamma} \quad \leadsto \quad \text{glide angle } \gamma$$

Apparent wind velocity

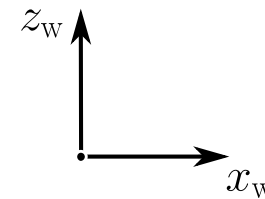
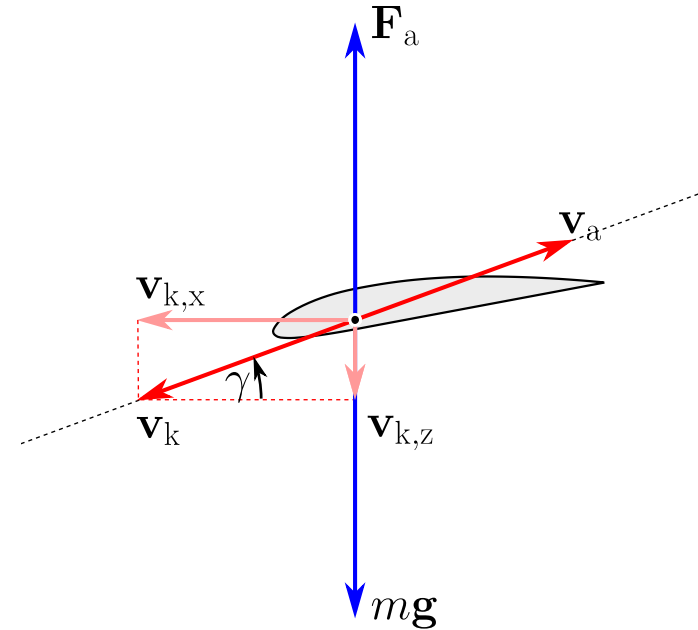
$$\mathbf{v}_a = \mathbf{v}_w - \mathbf{v}_k = -\mathbf{v}_k, \quad \text{with} \quad v_w = 0$$

Steady force equilibrium

$$m\mathbf{g} + \mathbf{F}_a = 0$$

Geometric similarity of kinematic and force triangles because $\mathbf{v}_{k,z} \parallel \mathbf{F}_a$ and $\mathbf{v}_k \parallel \mathbf{D}$

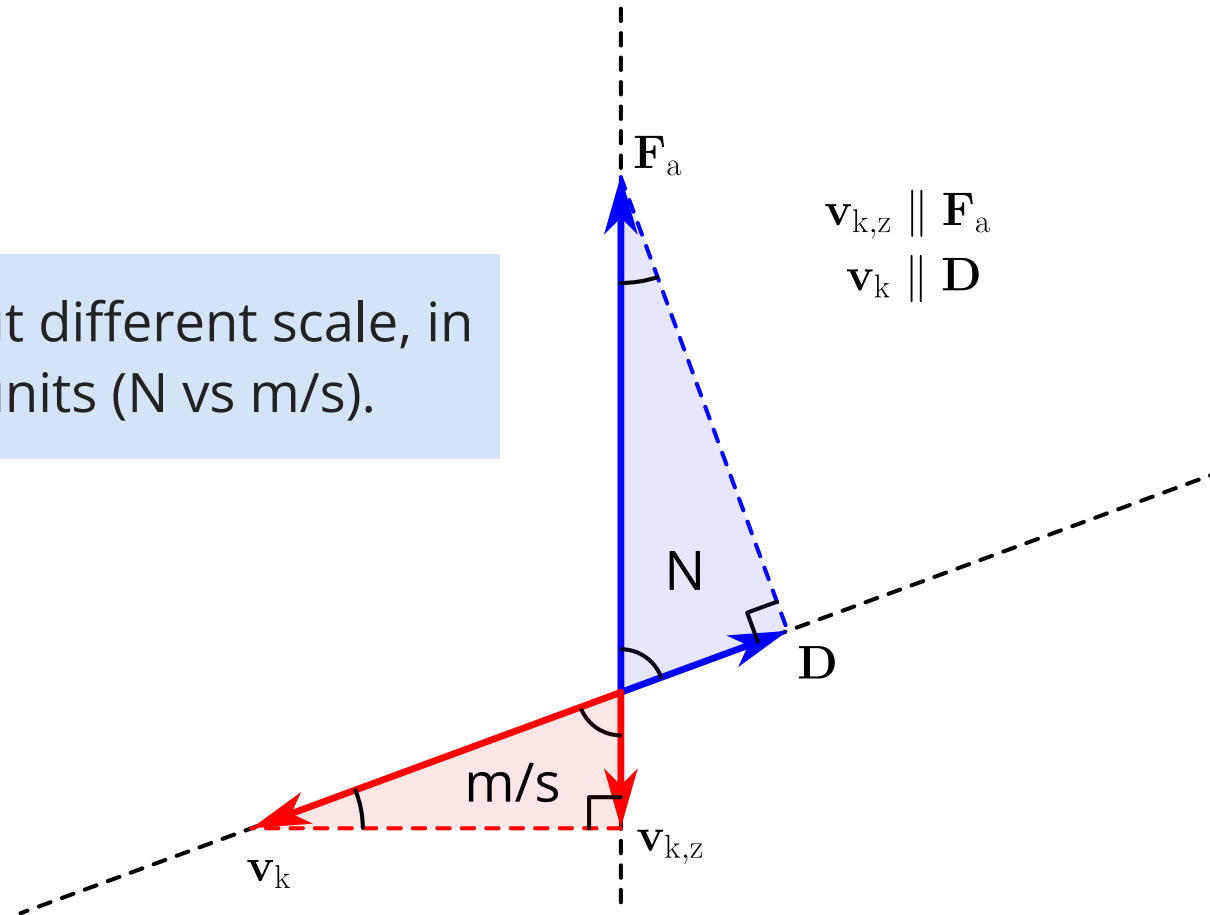
$$E = \frac{v_{k,x}}{v_{k,z}} = \frac{L}{D}$$





Geometric similarity

Same shape but different scale, in fact, different units (N vs m/s).



Uniform and constant wind

Effect of additional wind velocity $v_w > 0$

If wing flies against wind, glide angle γ gets steeper

Apparent wind velocity

$$\mathbf{v}_a = \mathbf{v}_w - \mathbf{v}_k$$

$$v_{a,x} = v_w - v_{k,x}$$

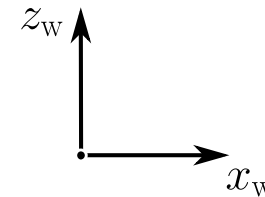
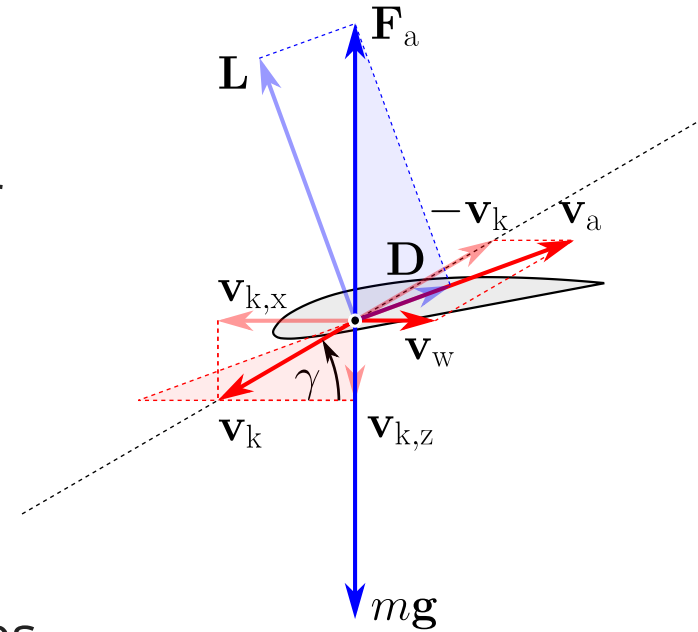
$$v_{a,z} = -v_{k,z}$$

Geometric similarity of kinematic and force triangles

$$E = \frac{v_{a,x}}{v_{a,z}} = \frac{L}{D}$$

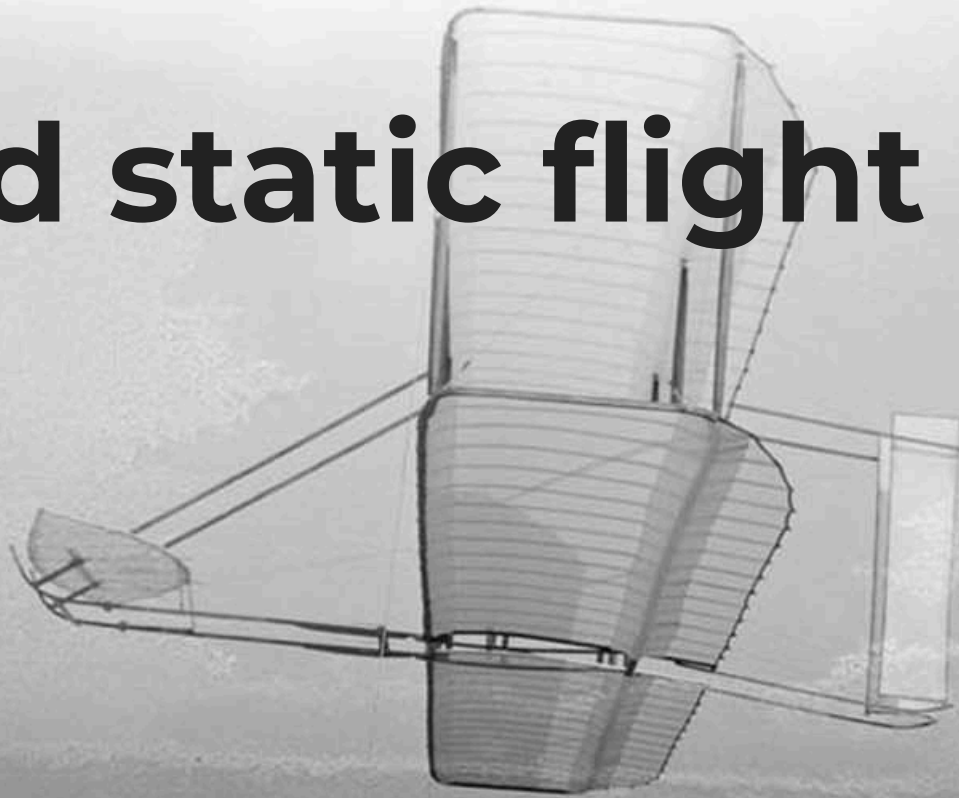
Application in AWE:

limiting case of retraction in pumping cycle with vanishing tether tension.





Tethered static flight



Dan Tate, left, and Wilbur Wright, right, flying the 1902 Wright glider as a kite, on 19 September 1902.





Static massless kite

Kite velocity

$$\mathbf{v}_k = 0$$

Apparent wind velocity

$$\mathbf{v}_a = \mathbf{v}_w - \mathbf{v}_k = \mathbf{v}_w$$

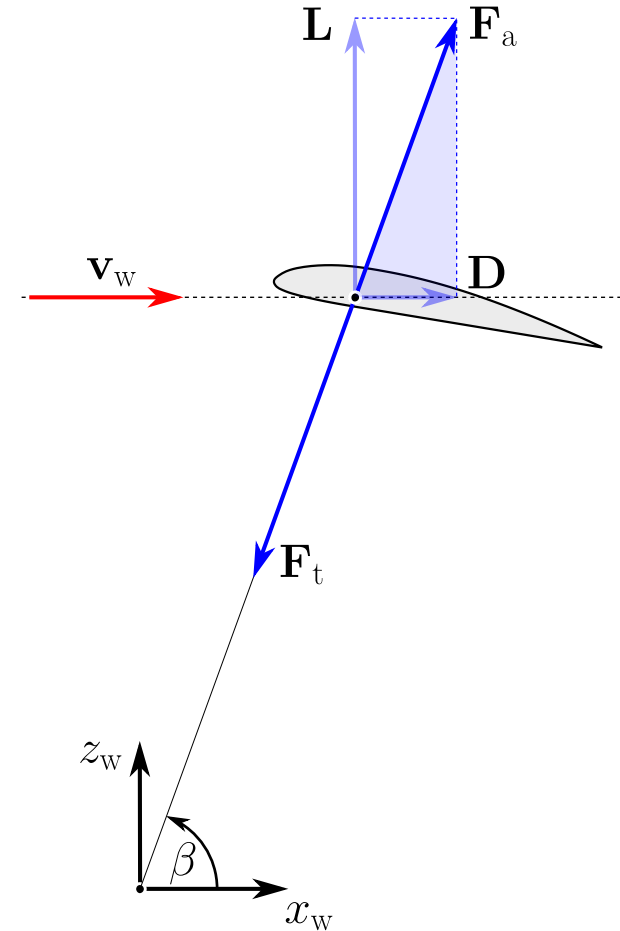
Static force equilibrium

$$\mathbf{F}_t + \mathbf{F}_a = 0$$

$$F_t = F_a = \sqrt{L^2 + D^2}$$

$$\tan \beta = \frac{L}{D}$$

$$\beta = \arctan E$$




$$\lim_{E \rightarrow \infty} \beta = \frac{\pi}{2}$$



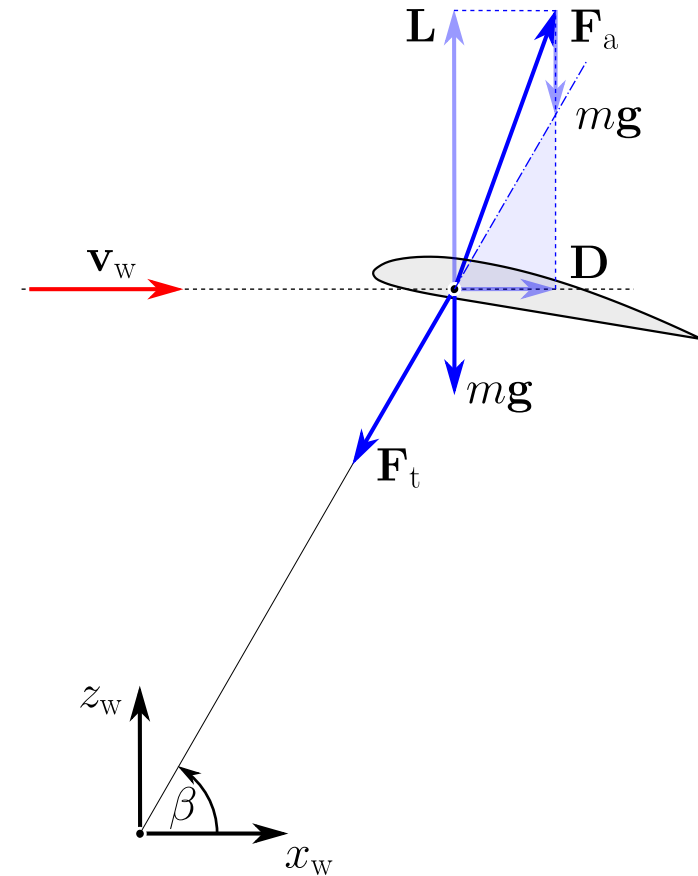

Effect of gravity

Static force equilibrium

$$\mathbf{F}_t + \mathbf{F}_a + m\mathbf{g} = 0$$

$$F_t = \sqrt{(L - mg)^2 + D^2}$$

$$\begin{aligned}\tan \beta &= \frac{L - mg}{D} \\ &= \frac{L}{D} \left[1 - \frac{mg}{L} \right] \\ &= E \left[1 - \frac{2gm}{\rho C_L S v_w^2} \right] \\ &= E \left[1 - \frac{\frac{2g}{\rho C_L} \frac{m}{S}}{v_w^2} \right]\end{aligned}$$



► But what is the physical meaning of $\frac{2g}{\rho C_L} \frac{m}{S}$?



Static take-off limit





Static take-off limit

Generated lift just balances the effect of gravity:

$$\frac{1}{2}\rho C_L S v_w^2 = mg$$

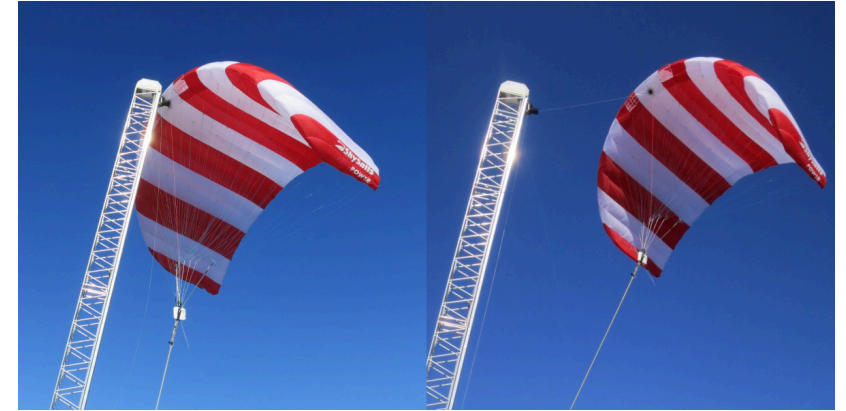
Equivalent to $\beta = 0$, i.e. horizontal tether force.

Solving for v_w leads to static take-off wind speed:

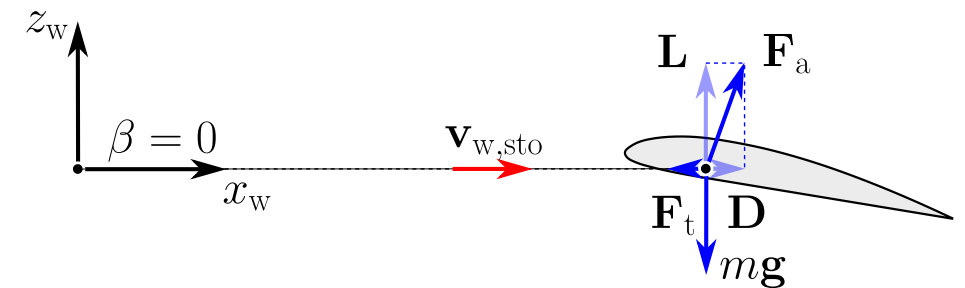
$$v_{w,\text{sto}} = \sqrt{\frac{2g}{\rho C_L} \frac{m}{S}}$$

Mass-to-area ratio m/S is an important scaling parameter affecting take-off limit

Definition identical to the stall speed v_{stall} of an aircraft ([Anderson 2016](#)).



SkySails' launch from a static mast





Effect of gravity

Static force equilibrium

$$\mathbf{F}_t + \mathbf{F}_a + m\mathbf{g} = 0$$

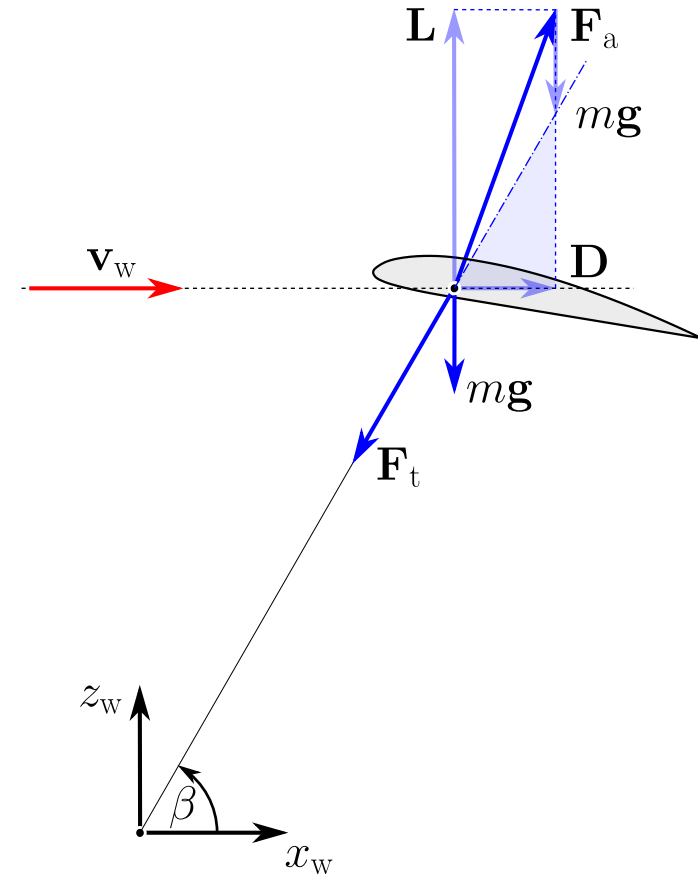
$$F_t = \sqrt{(L - mg)^2 + D^2}$$

$$\begin{aligned} \tan \beta &= \frac{L - mg}{D} \\ &= \frac{L}{D} \left[1 - \frac{mg}{L} \right] \\ &= E \left[1 - \frac{2gm}{\rho C_L S v_w^2} \right] \\ &= E \left[1 - \frac{\frac{2g}{\rho C_L} \frac{m}{S}}{v_w^2} \right] \end{aligned}$$



$$= E \left[1 - \left(\frac{v_{w,sto}}{v_w} \right)^2 \right], \quad \text{with}$$

$$v_{w,sto} = \sqrt{\frac{2g}{\rho C_L} \frac{m}{S}}$$





Static take-off wind speed

Kite	S (m ²)	m (kg)	$C_{L,max}$ (-)	m/S (kg/m ²)	$v_{w,sto}$ (m/s)
Ampyx AP2	3	35	1.5	11.7	11.3
Mozaero AP3	12	475	2.1	39.6	17.5
Makani MX2	54	1850	2	34.3	16.7
MegAWES	150.45	6885	1.9	45.8	19.8
TU Delft V3	19.75	22.8	0.88	1.15	4.6
Kitepower V9	47	73	1.19	1.55	4.6

Source: Joshi et al. (2024)





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<https://doi.org/10.5194/wes-2025-77>



Questions?

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