Airborne Wind Energy

Energy harvesting with kites

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Outlines

- Announcements
- Content
- Pumping cycle operation
- Pumping cycle model



Learning objectives

The focus of this lecture is on the **pumping cycle** operation that most of the currently implemented AWE systems use. Operational **strategies** are discussed, including now also **winch control**. Relevant literature source is Luchsinger (2013).

Announcements

- 20 November 2026: AWE computational workshop.
  - Instructor: Oriol Cayon
  - Requirements: laptop with internet connection
  - The workshop is a Jupyter notebook, via platform independent Binder.
  - As a backup, please install vscode and a recent Python installation.

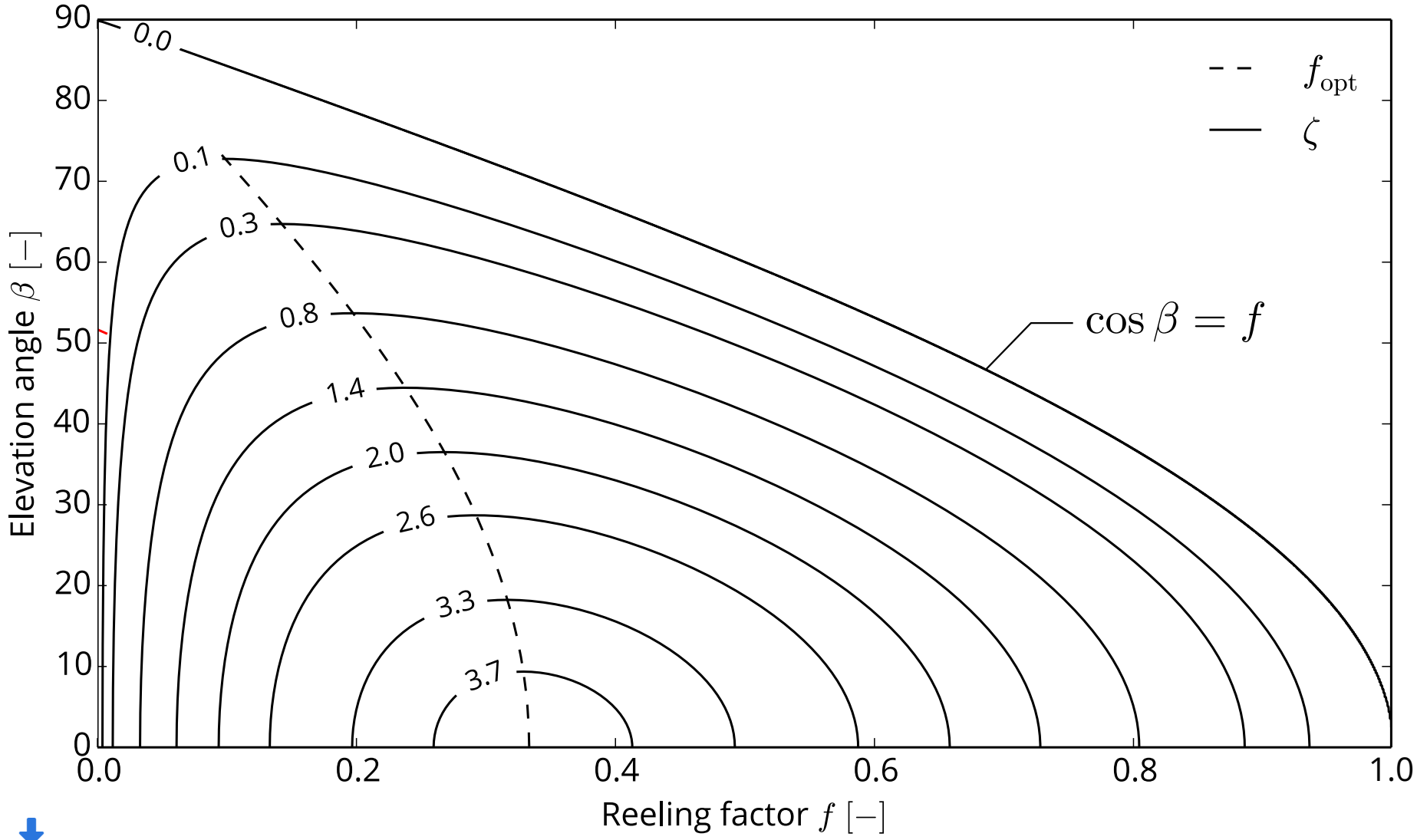
Content

- Revisit theory in three dimension (separate slide deck)
- Revisit power plot example

- Pumping cycle operation
- Traction phase (velocity & force triangles) for non-crosswind case
- Retraction phase (velocity & force triangles)
- Depower
- Steady-state retraction as an idealization
- Transition phases
- Operational strategies (Luchsinger 2013)

Power plot example

$m = 0, \phi = 0, \chi = 90°, E = 5, C_L = 1$



Schmehl et al. (2013)

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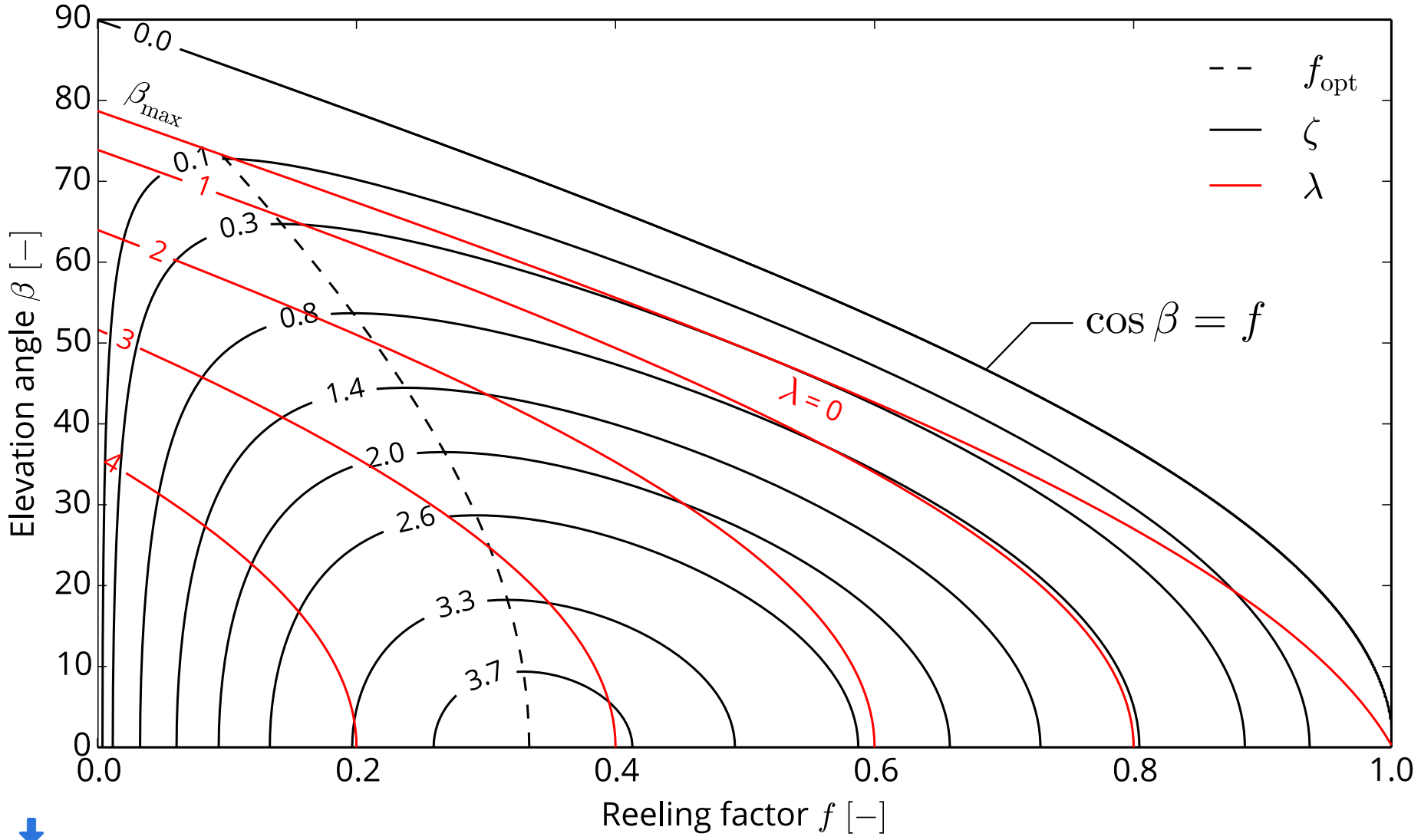

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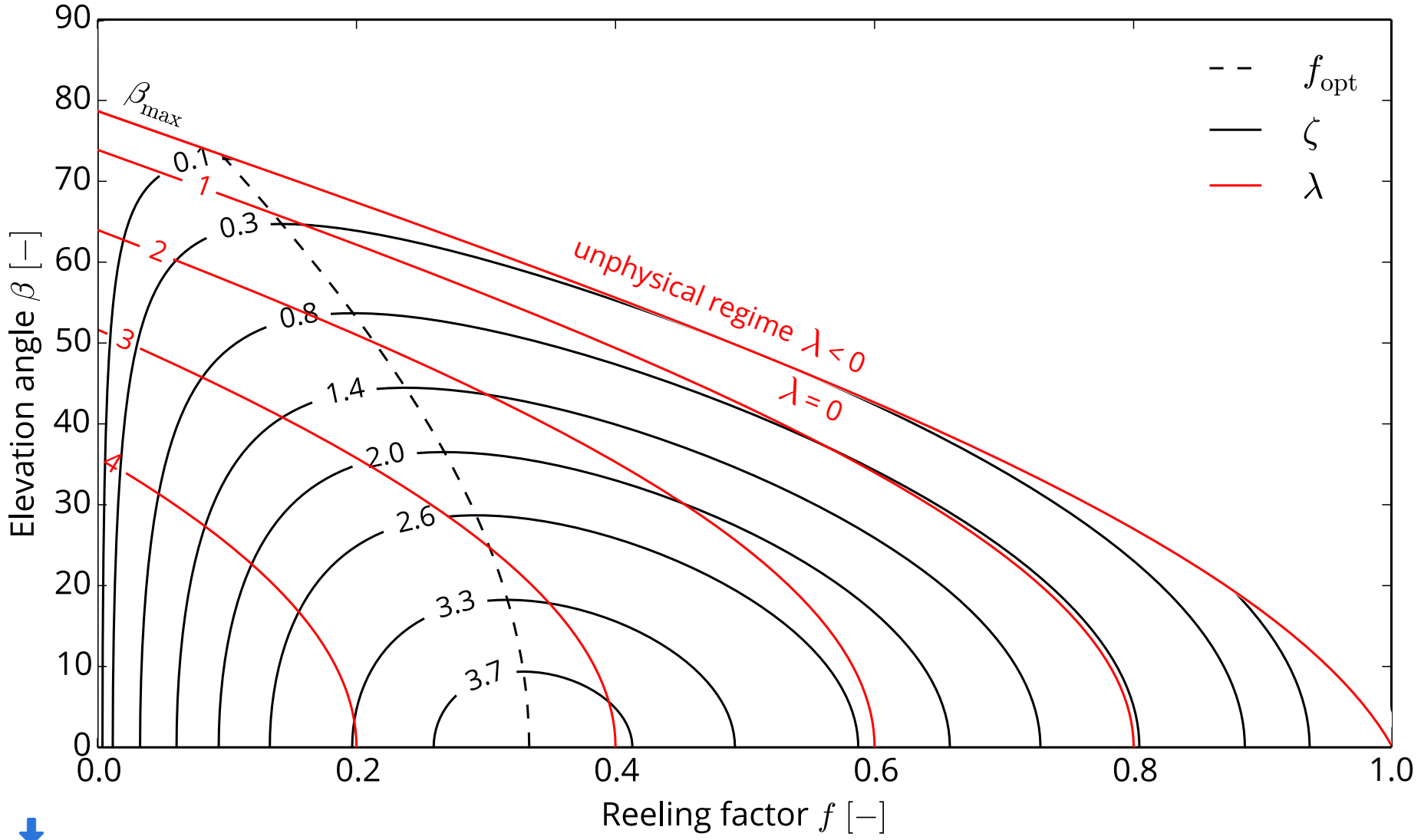

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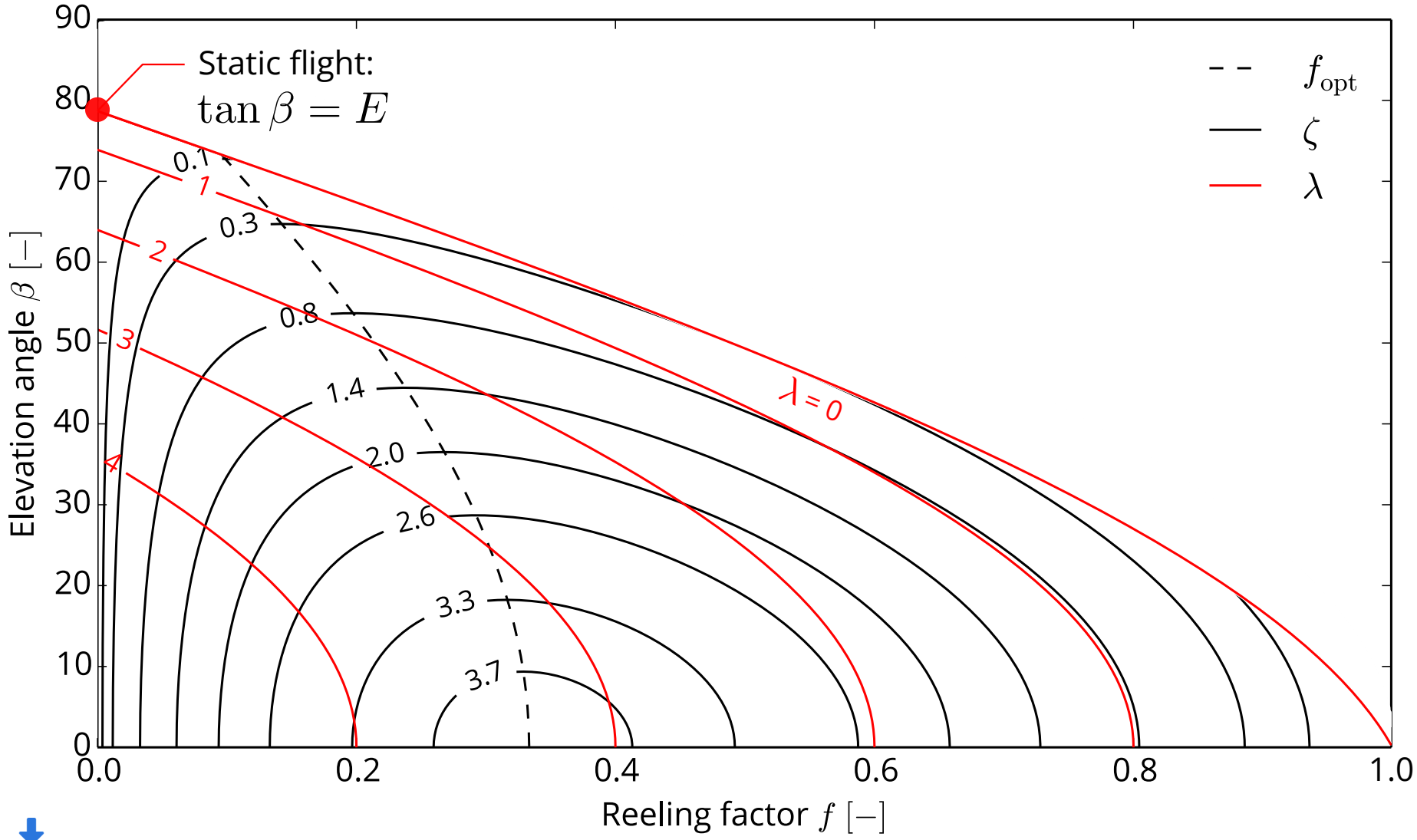

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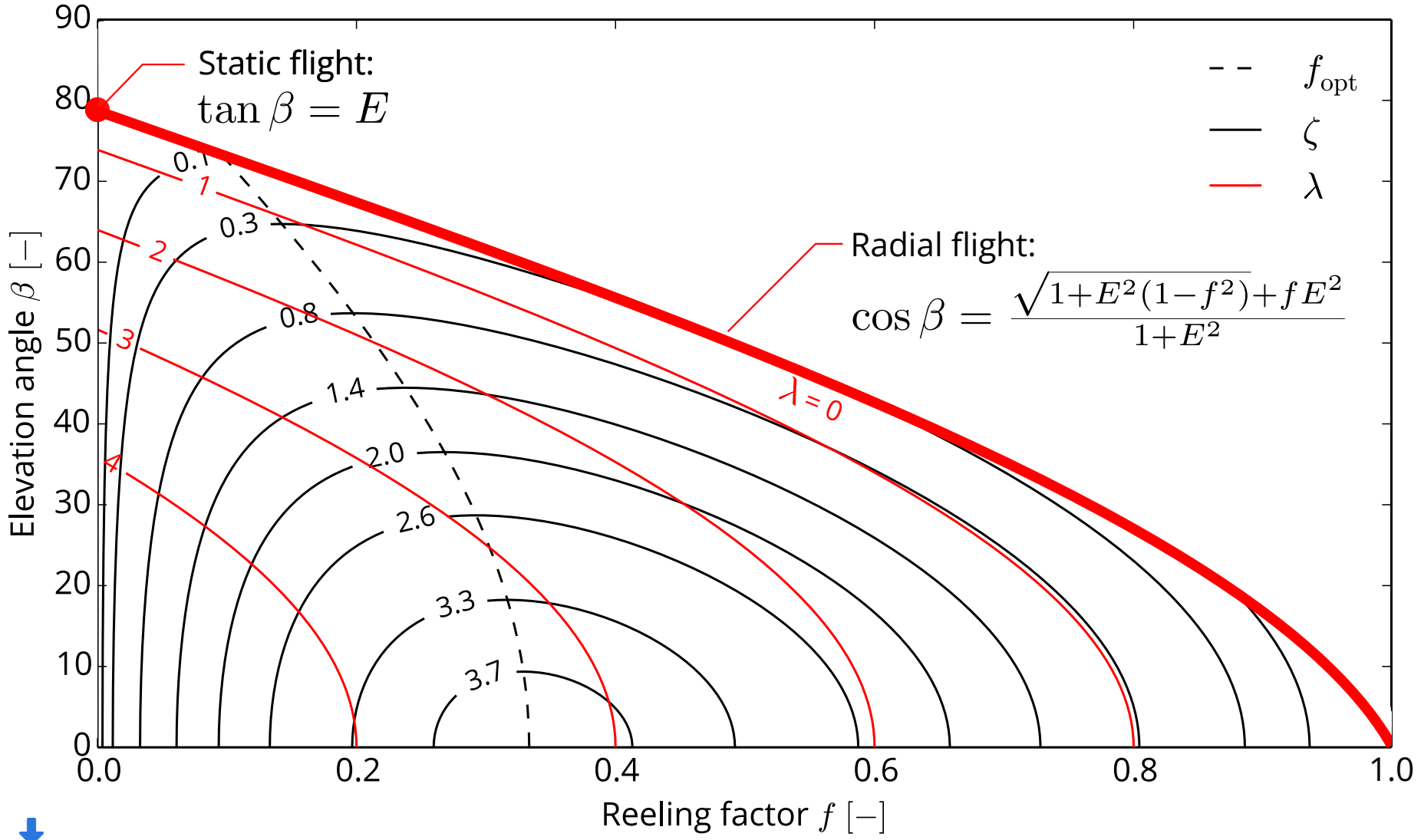

Schmehl et al. (2013)

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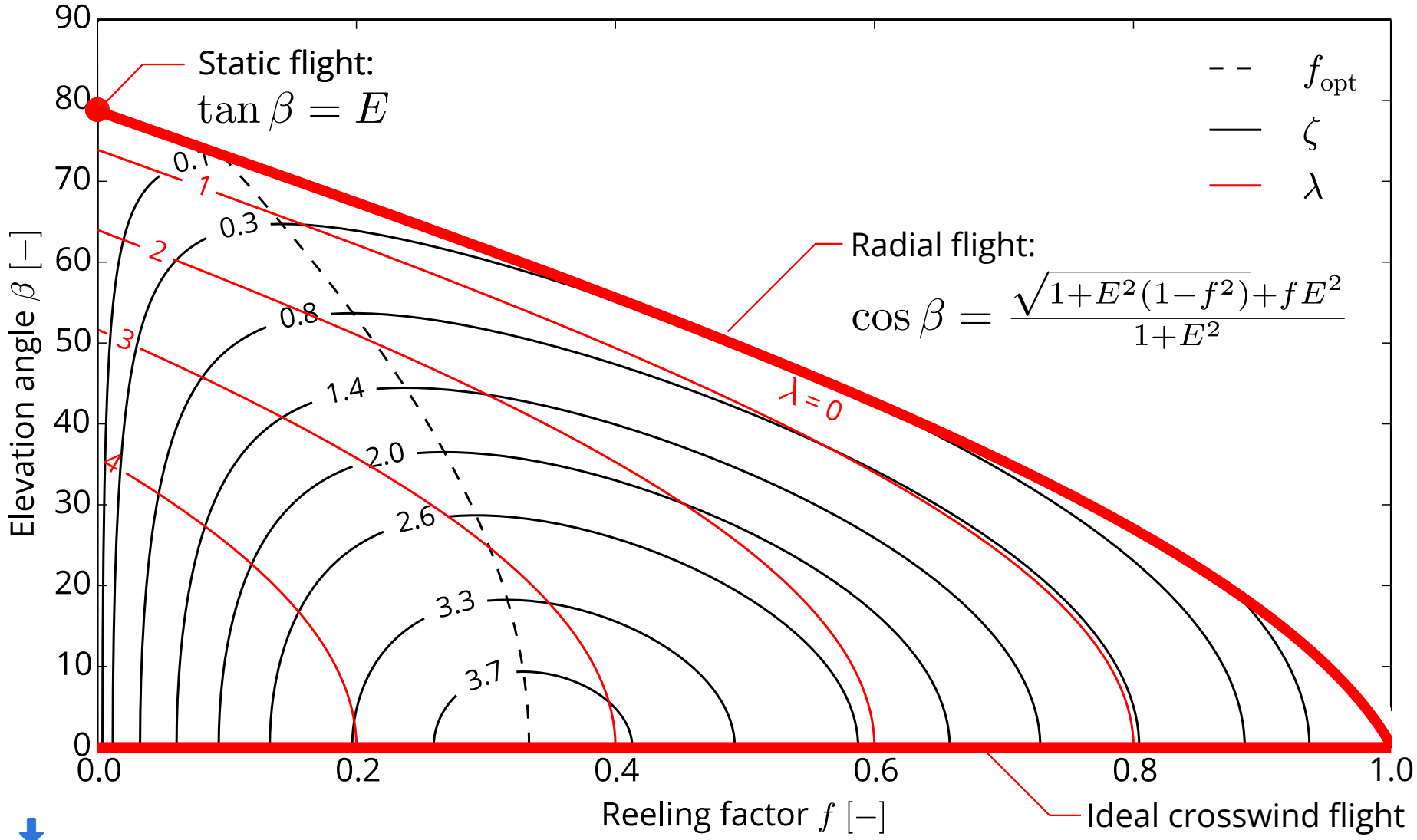


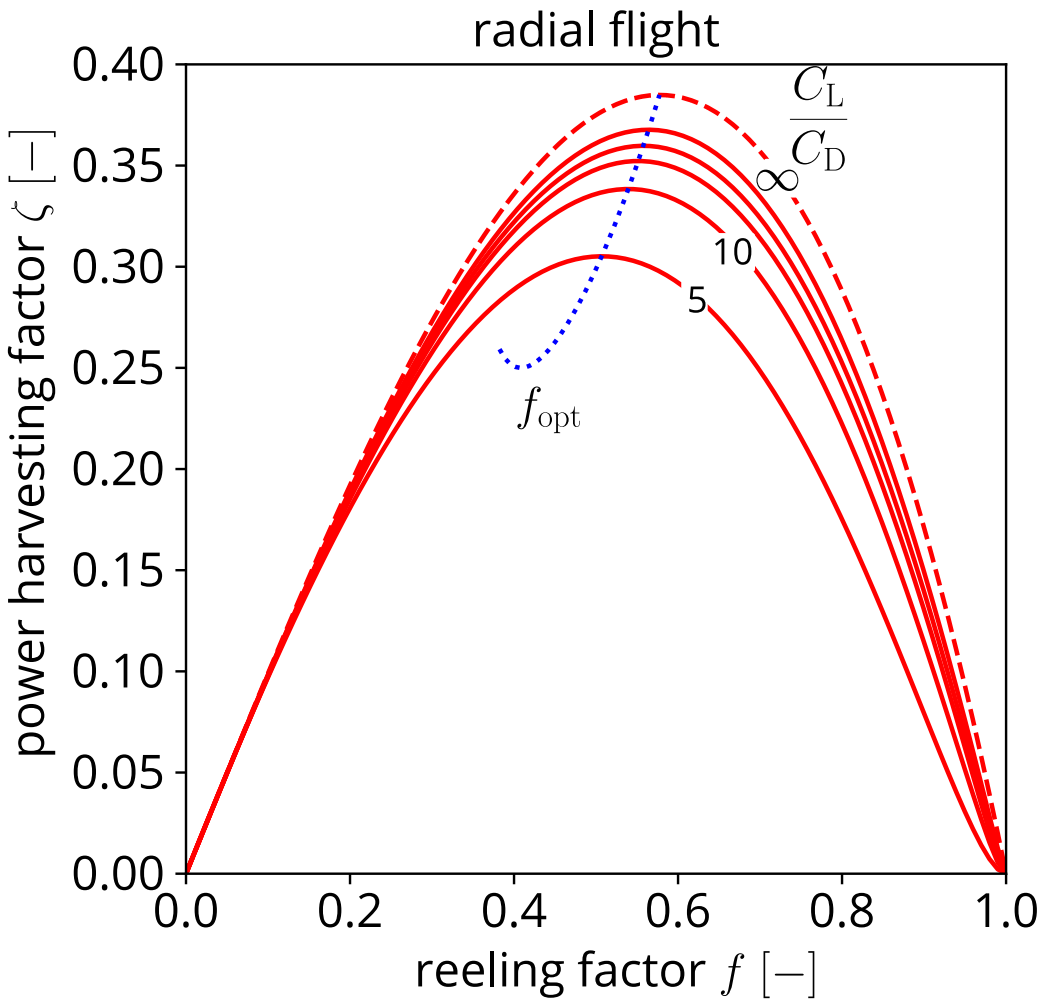
Schmehl et al. (2013)

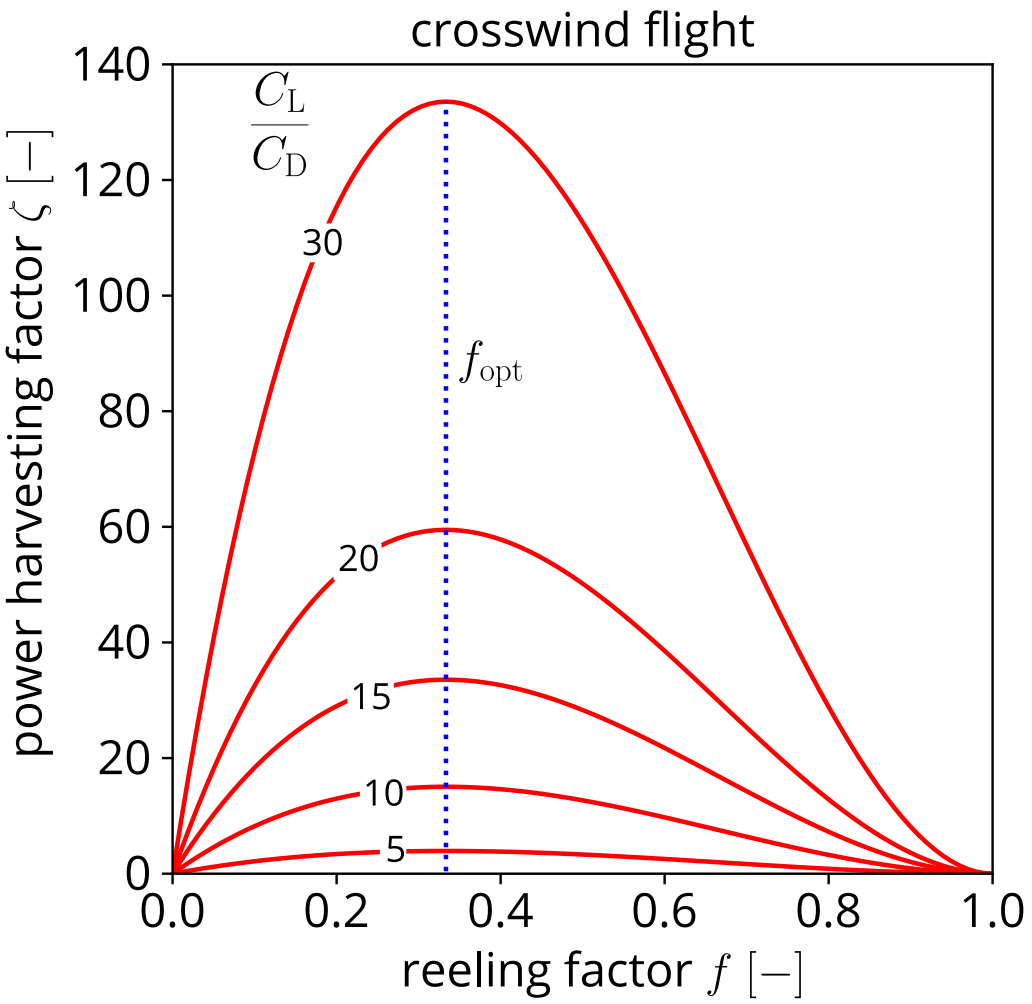
Unphysical power plot region

> The region between $\cos\beta = f$ and $\lambda = 0$ presents a solution of very low values $\zeta > 0$.
>
> But why are these unphysical solutions?

- The solutions in this regions imply $v_{\mathrm{k},\tau} < 0$.
- However, the tangential kite velocity is limited to ranges of $v_{\mathrm{k},\tau} \geq 0$.
- The asymptotic limiting case is radial flight, with a finite minimum value $\zeta > 0$.

Loyd's theory - comparison

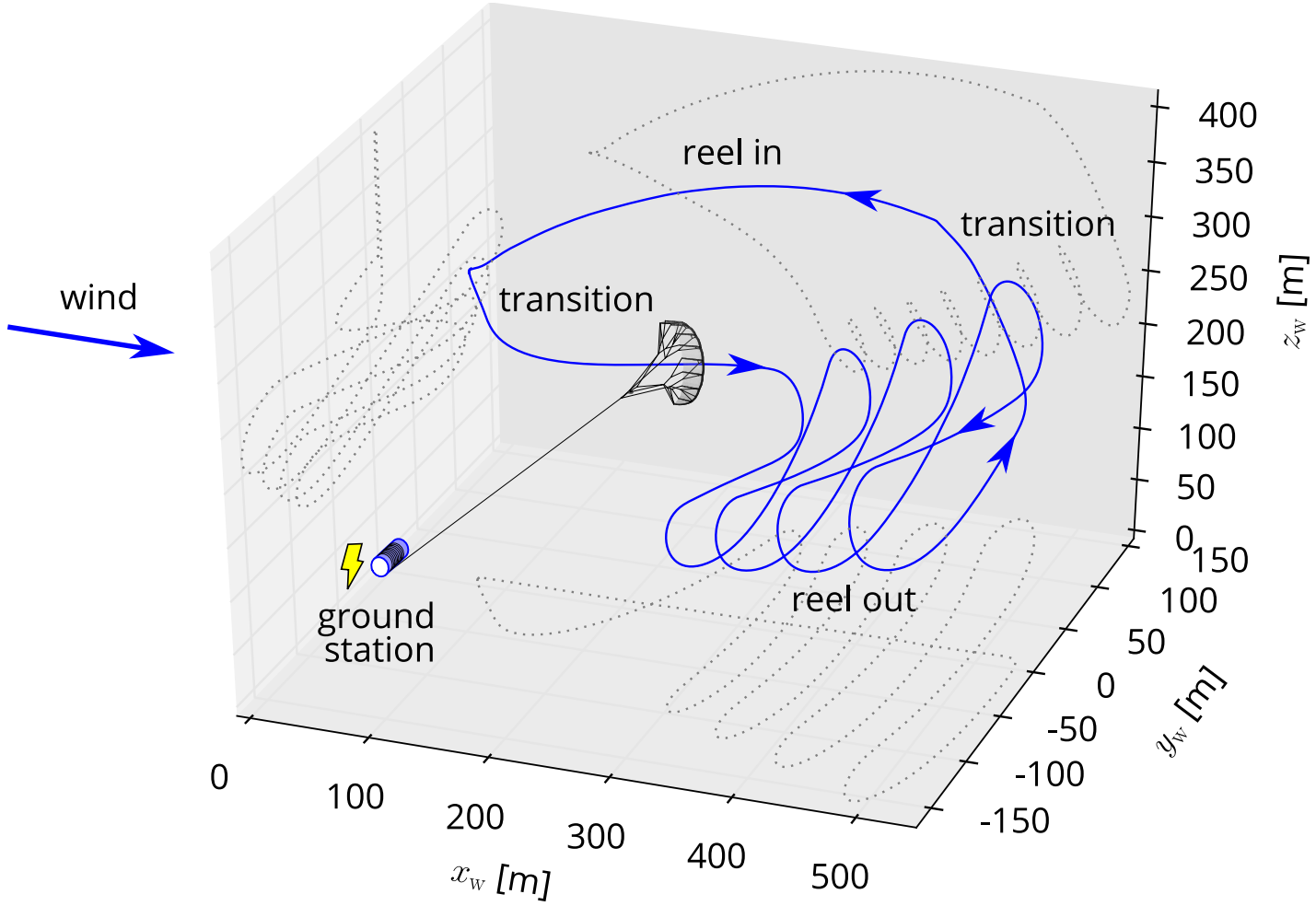




awesco.eu/awe-explained/

Pumping cycle operation

Pumping cycle simulation



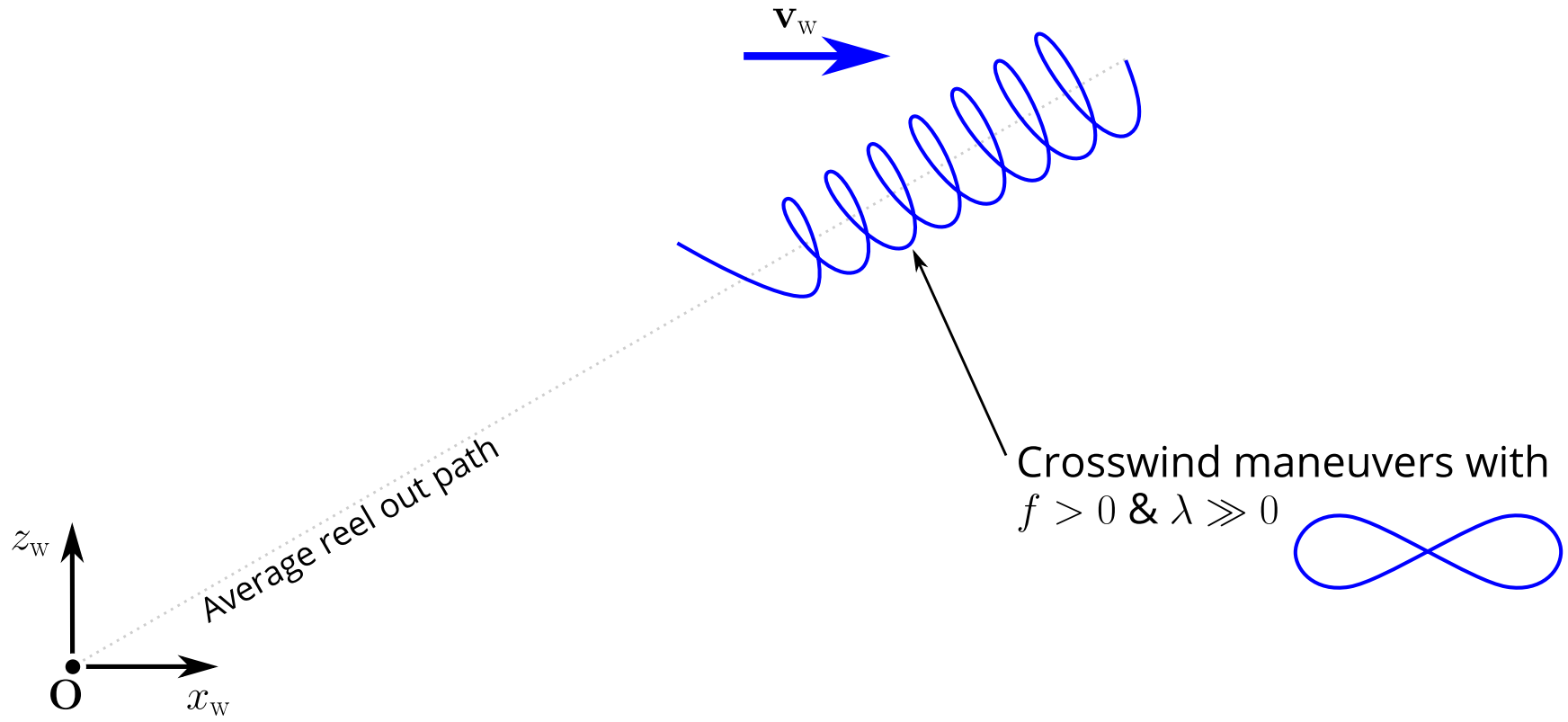
Simulation results by Fechner (2016).

Pumping cycle visualization



Courtesy of Kitepower B.V. (2018)

Pumping cycle idealization



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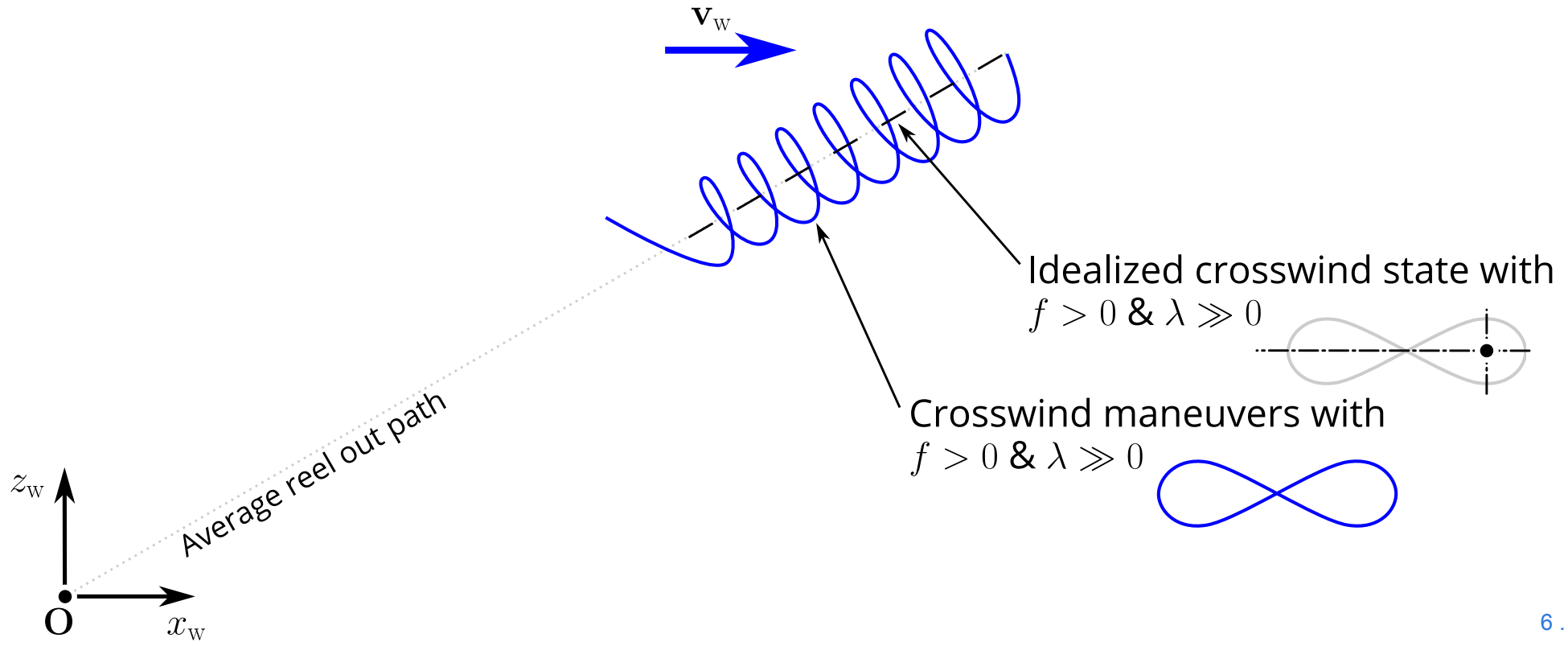

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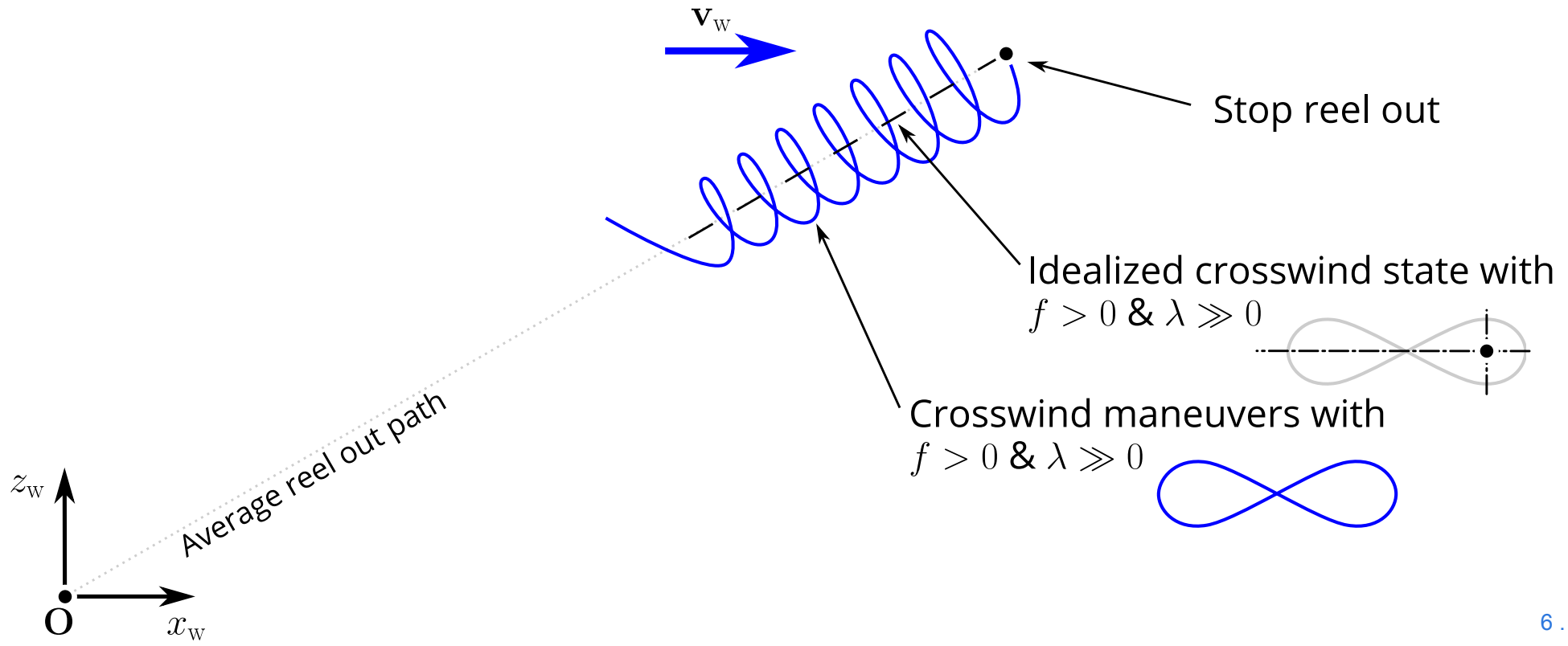

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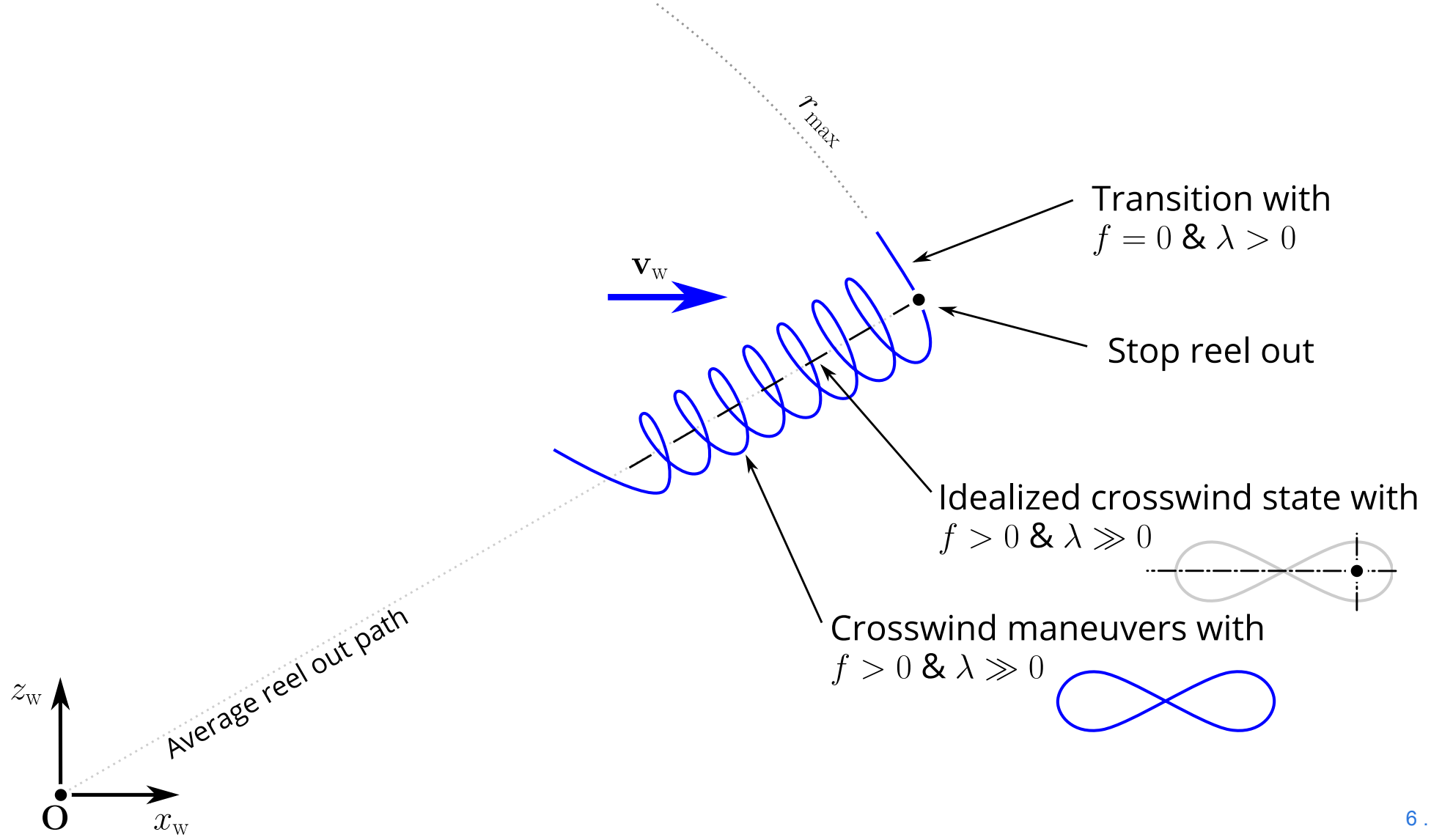

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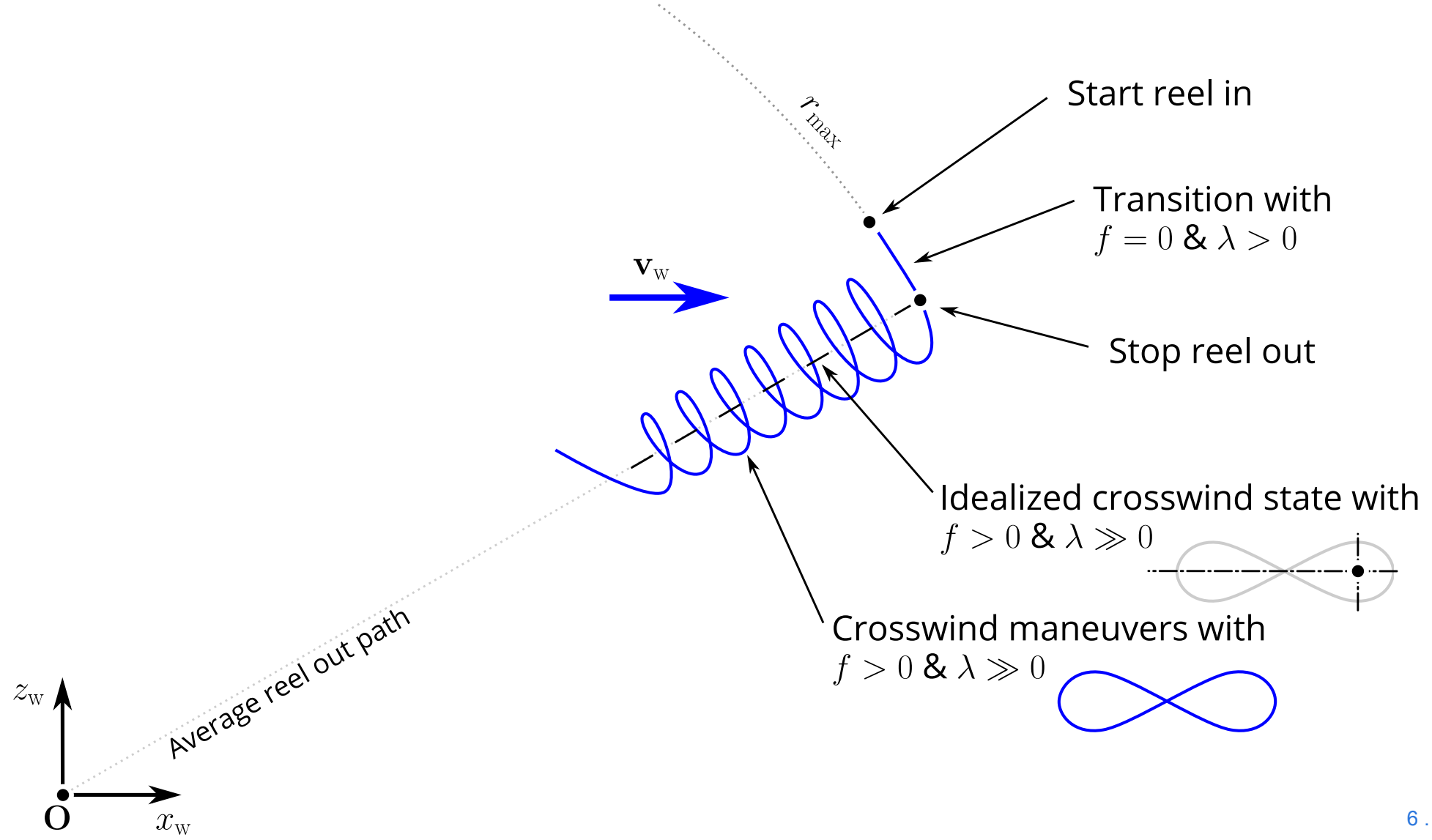

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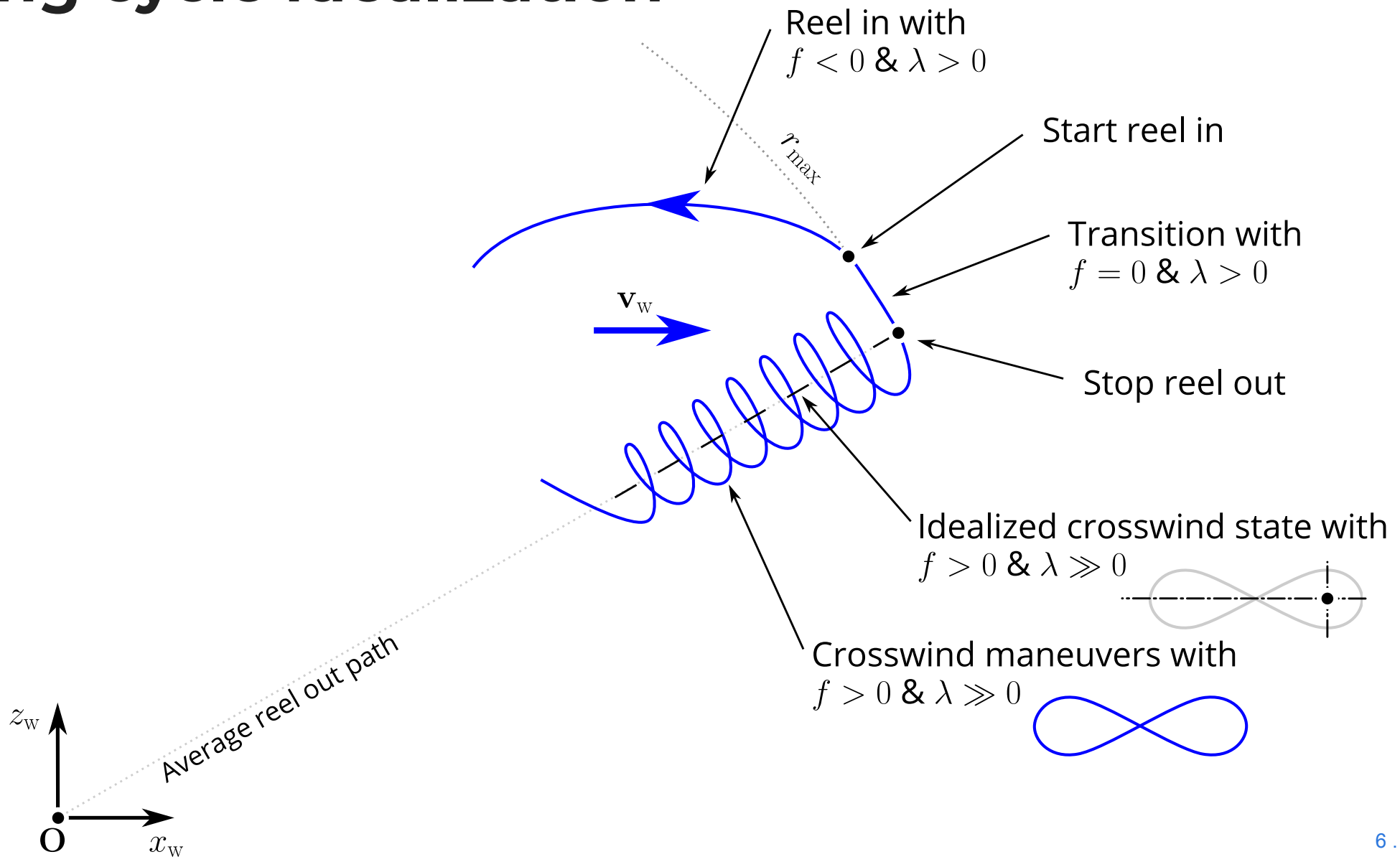

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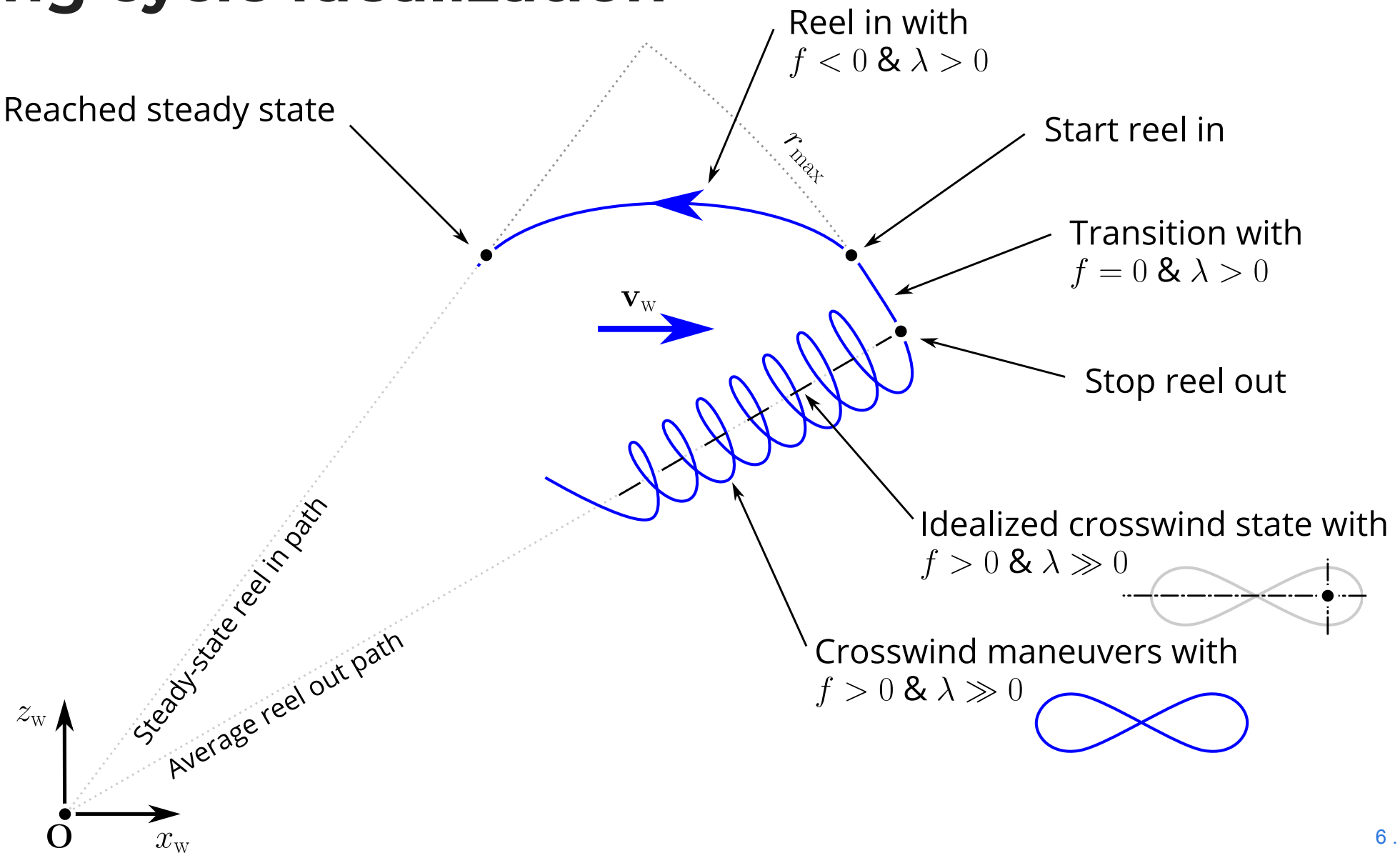

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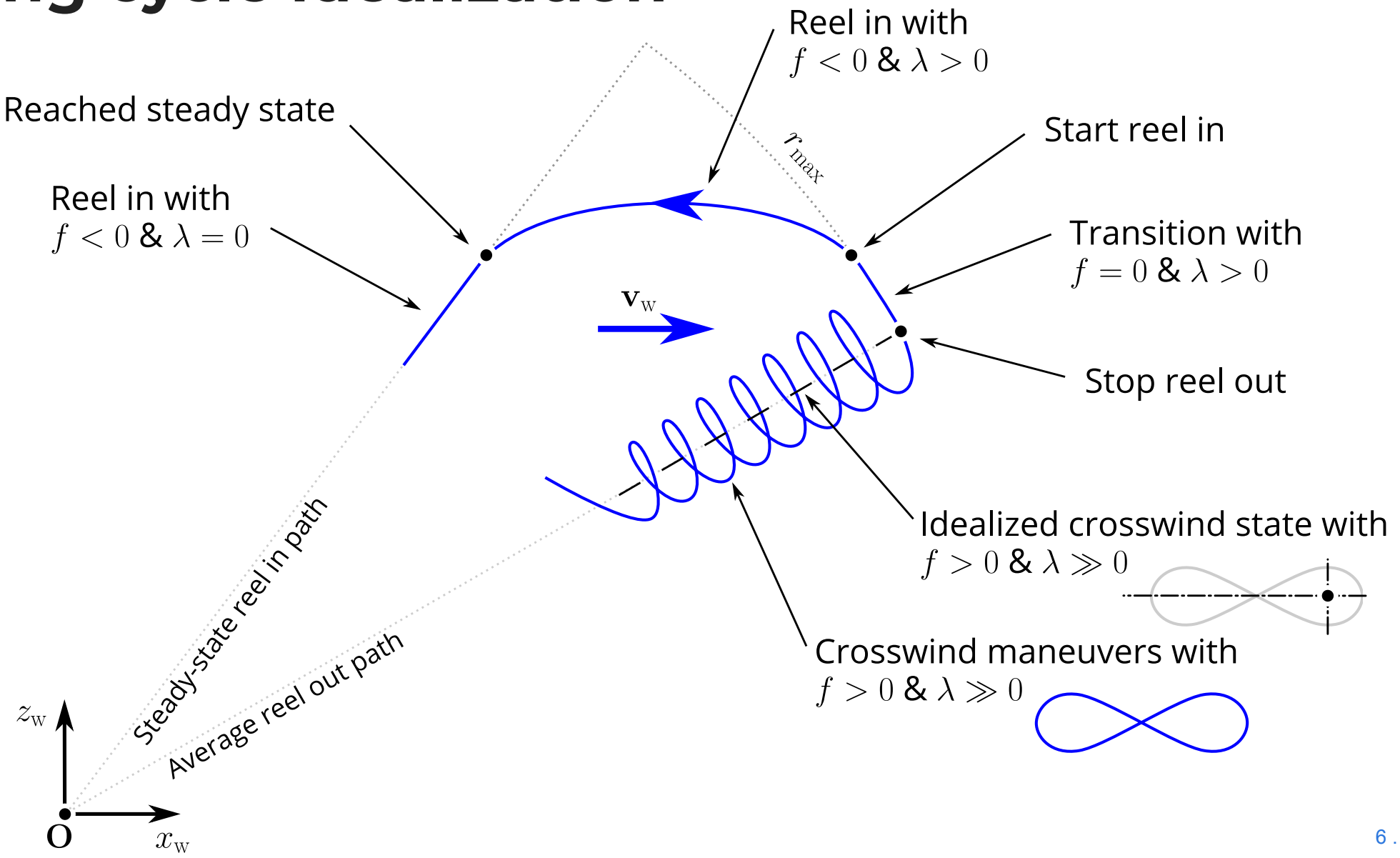

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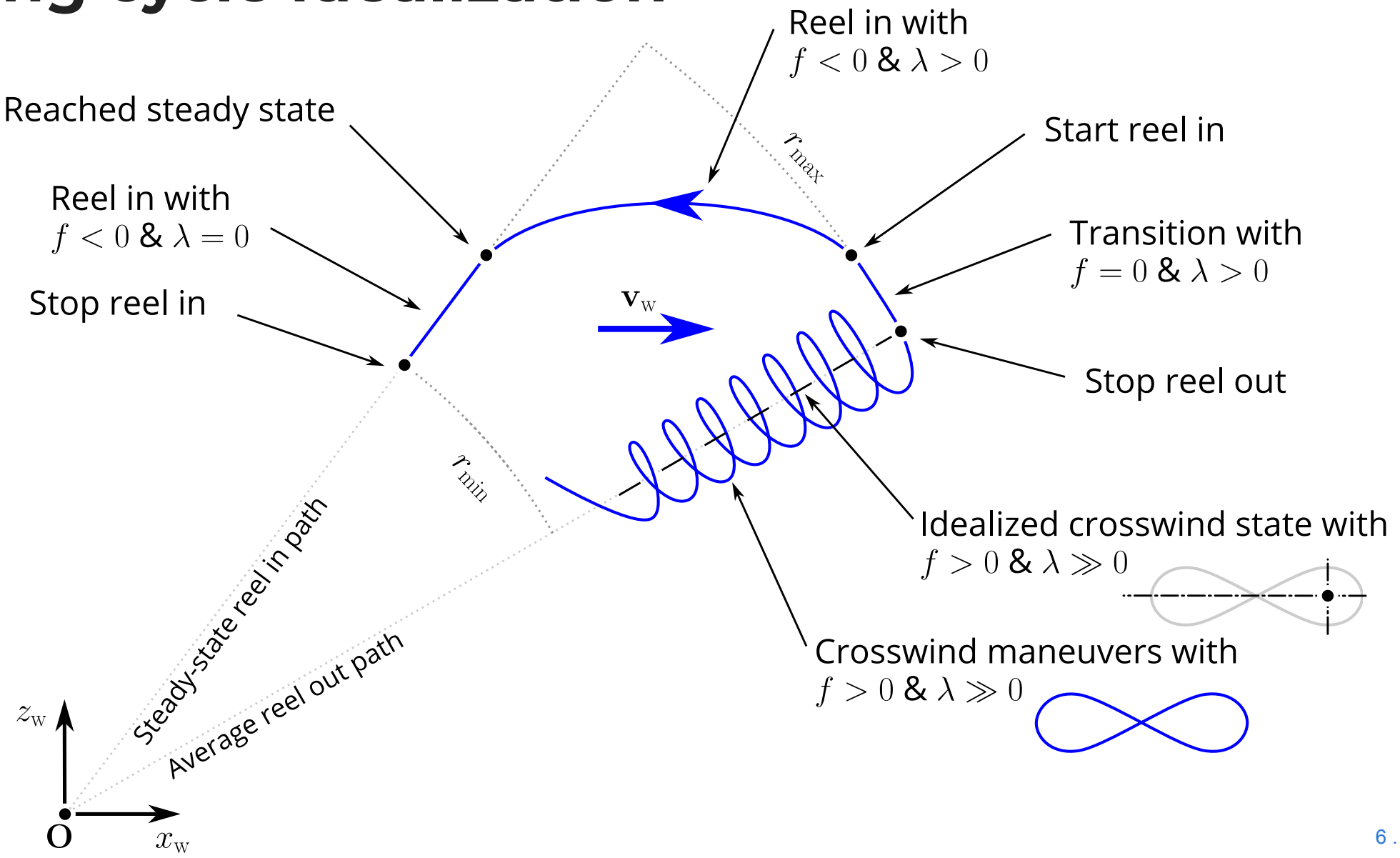

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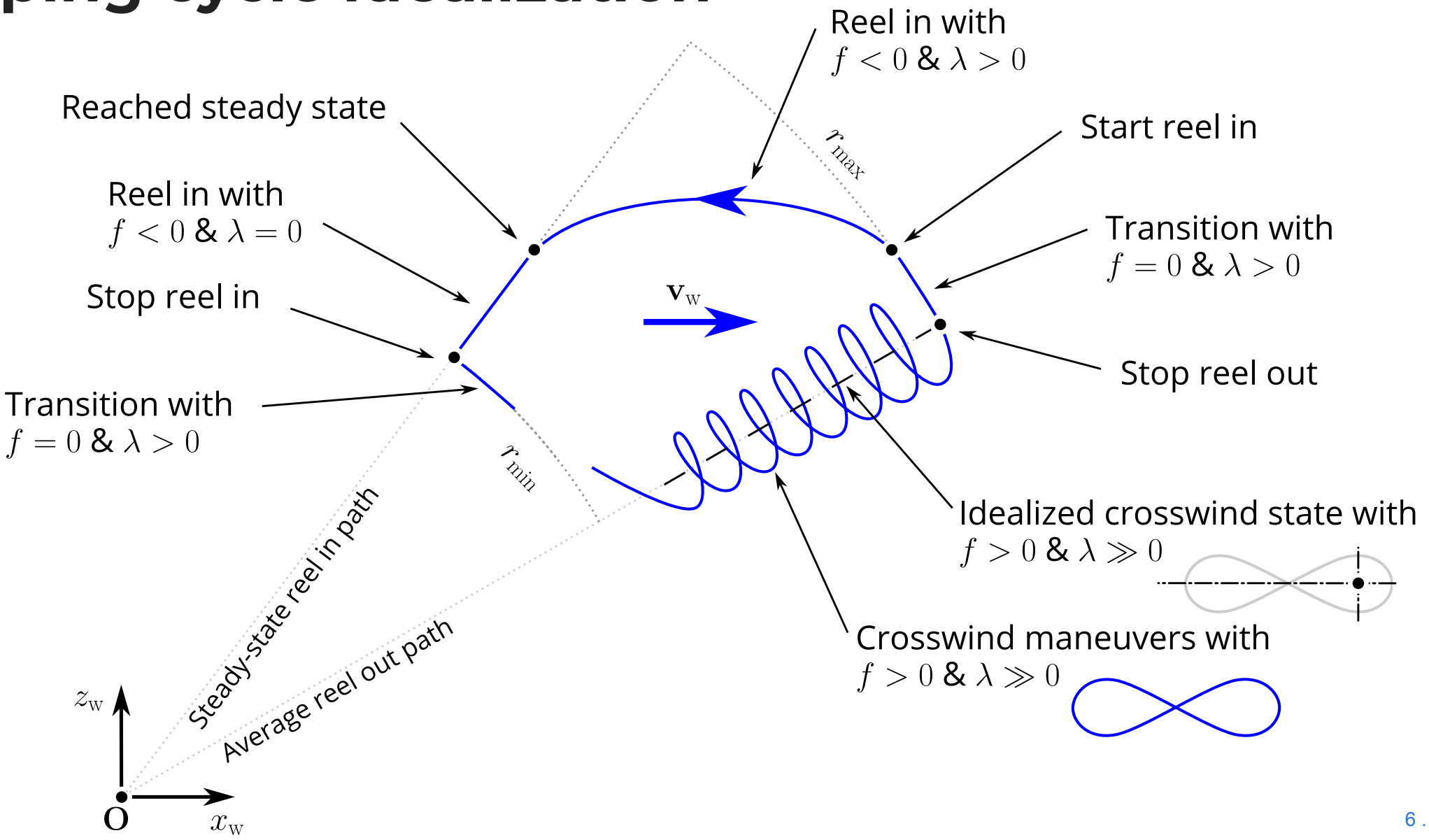

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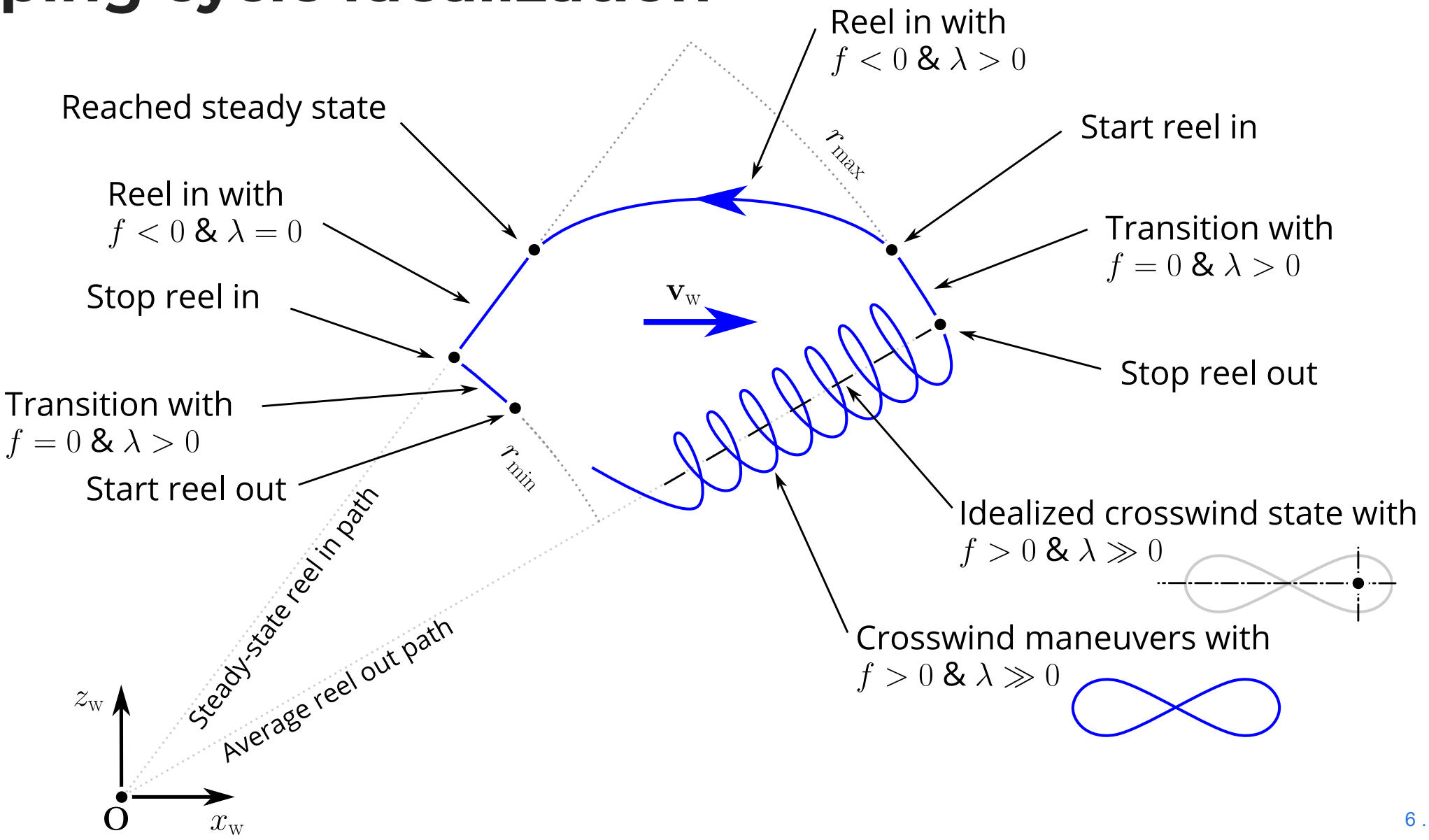

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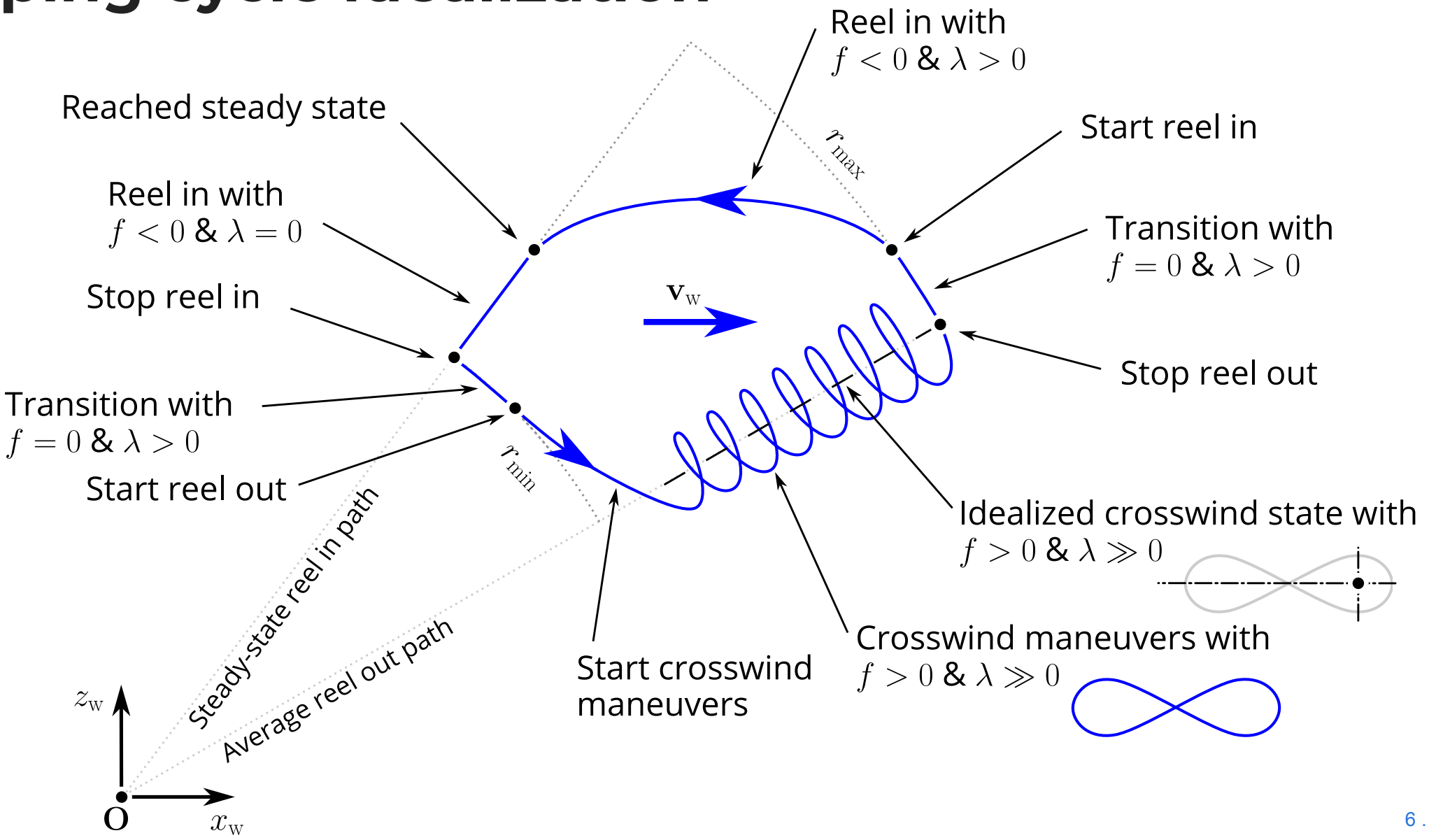
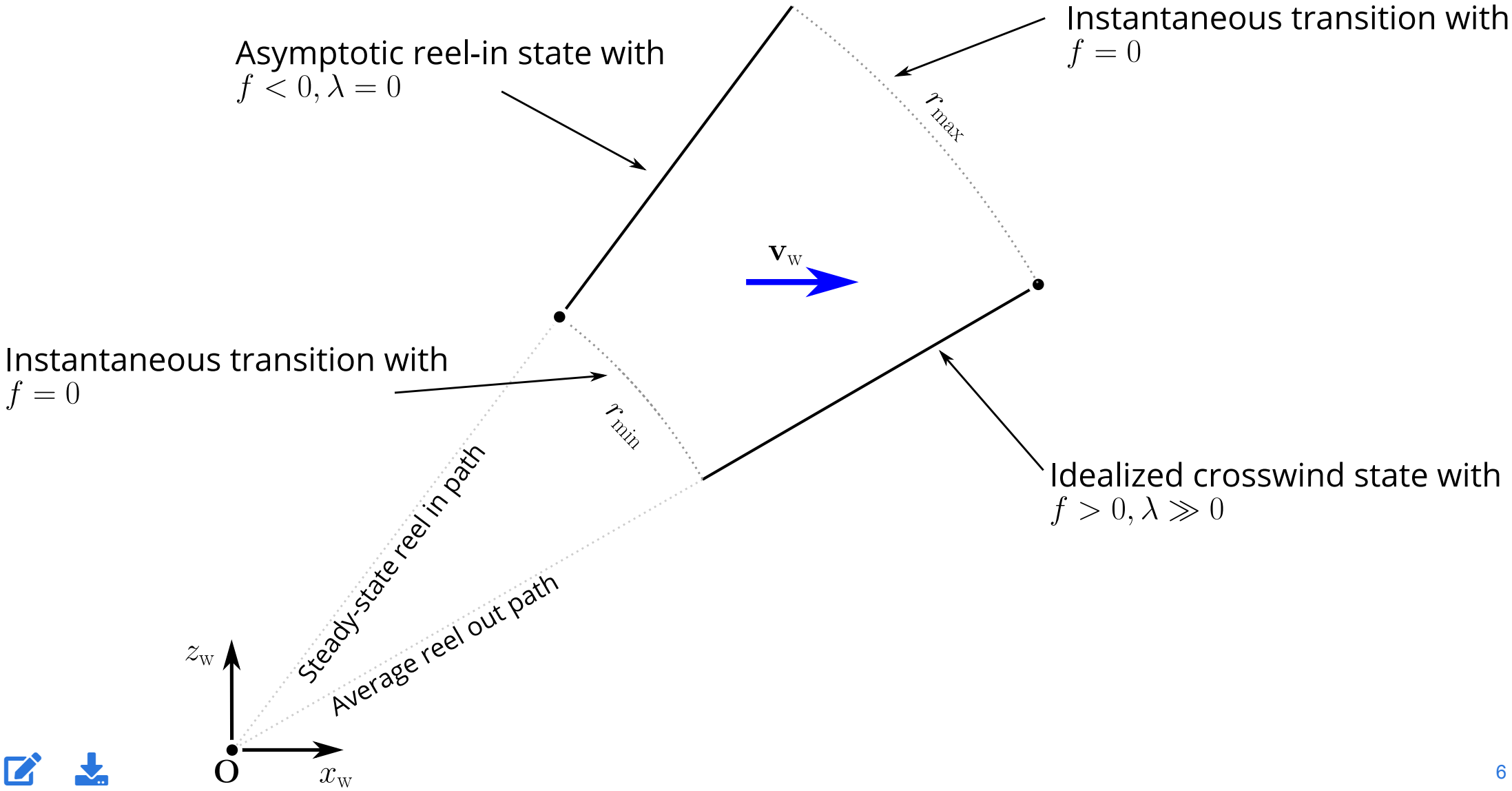


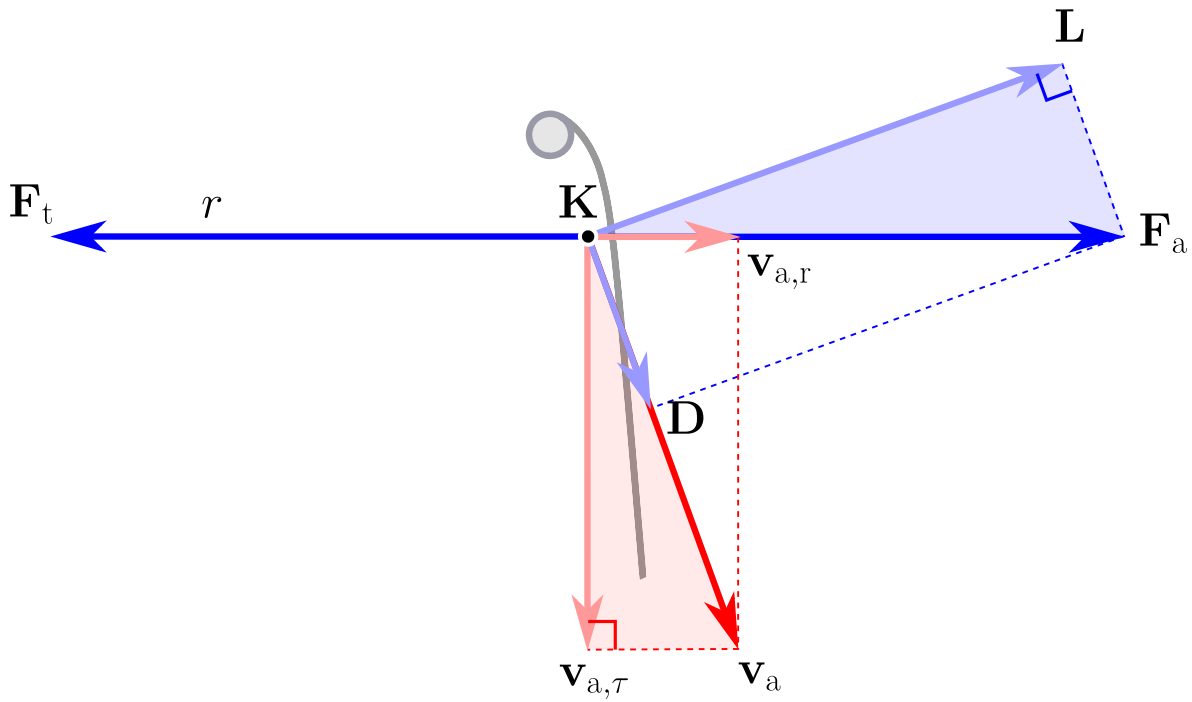
Pumping cycle two-state approximation



Pumping cycle model

Reel-out state

Representative reel-out state defined by β, ϕ and f

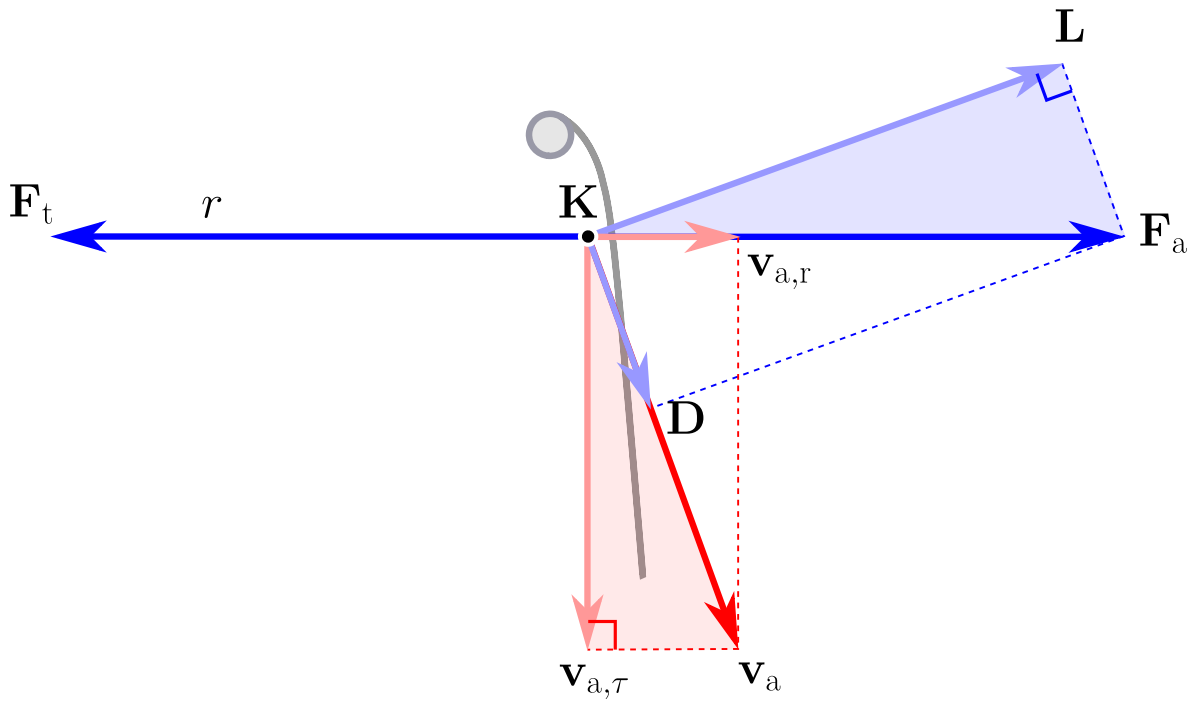


Reel-out state

Representative reel-out state defined by β, ϕ and f

Apparent wind speed

$$\frac{v_\mathrm{a}}{v_\mathrm{w}} = \sqrt{1+E^2}\,(\cos\beta\cos\phi - f)$$



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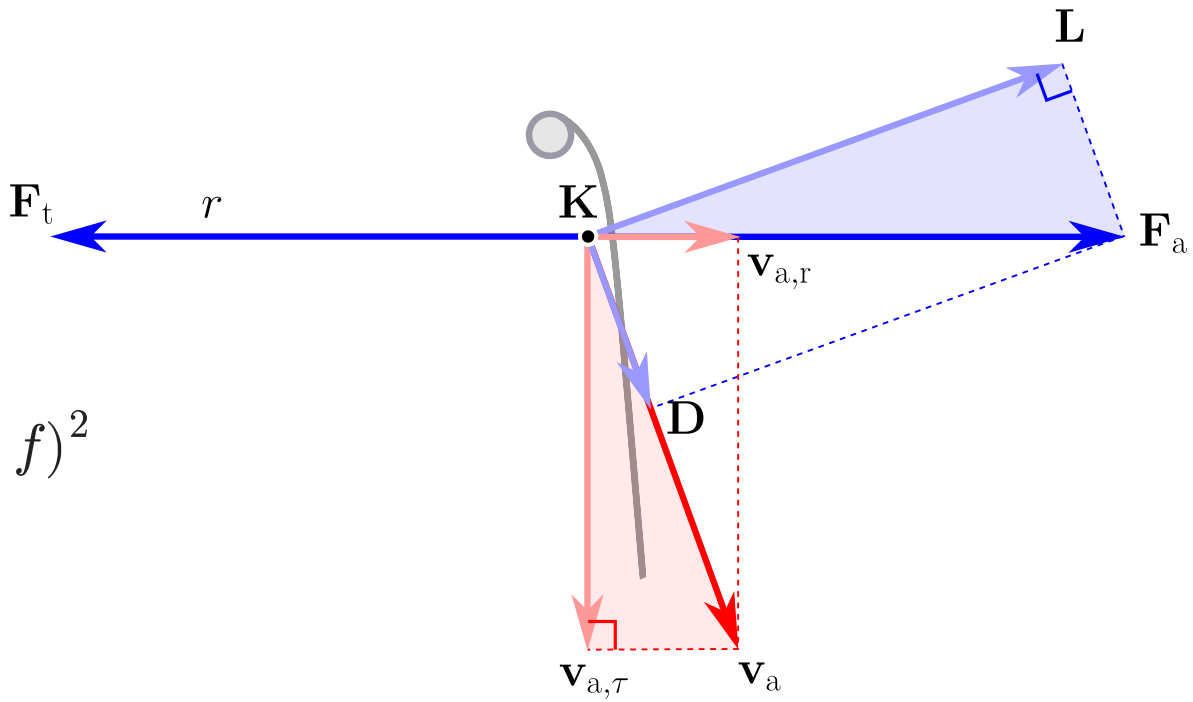
Tether force

$$\frac{F_\mathrm{t}}{qS} = C_\mathrm{L}\sqrt{1+\frac{1}{E^2}}\left(1+E^2\right)\left(\cos\beta\cos\phi - f\right)^2$$



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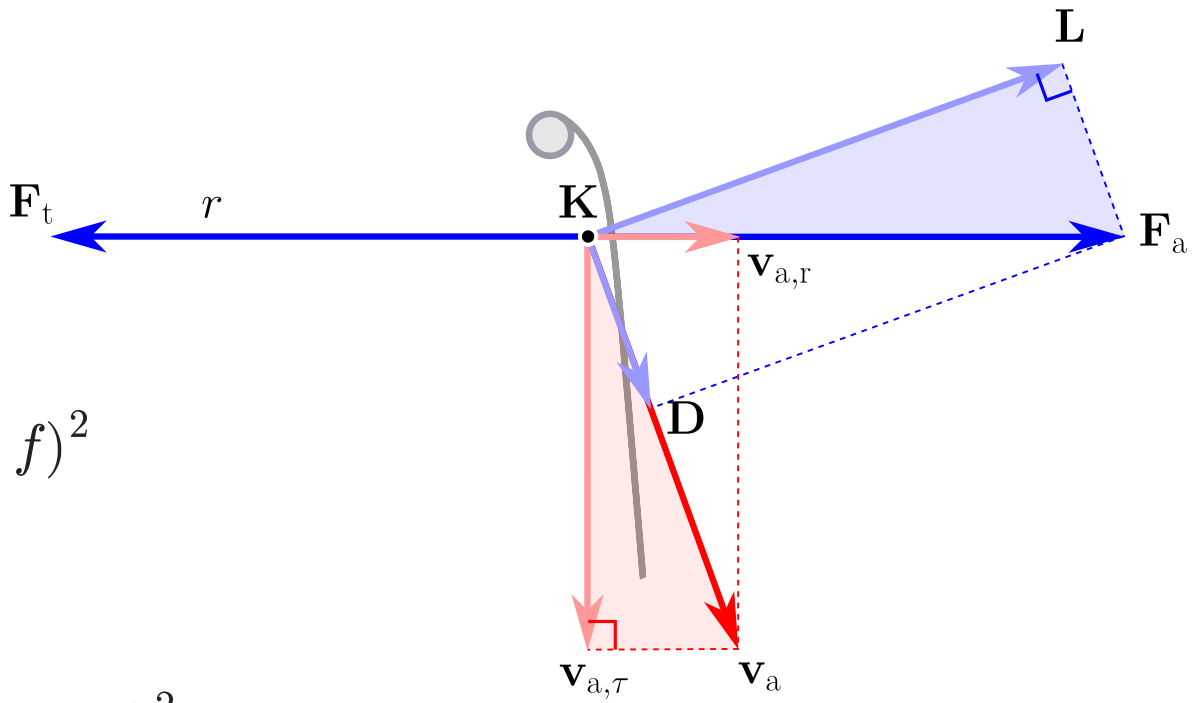
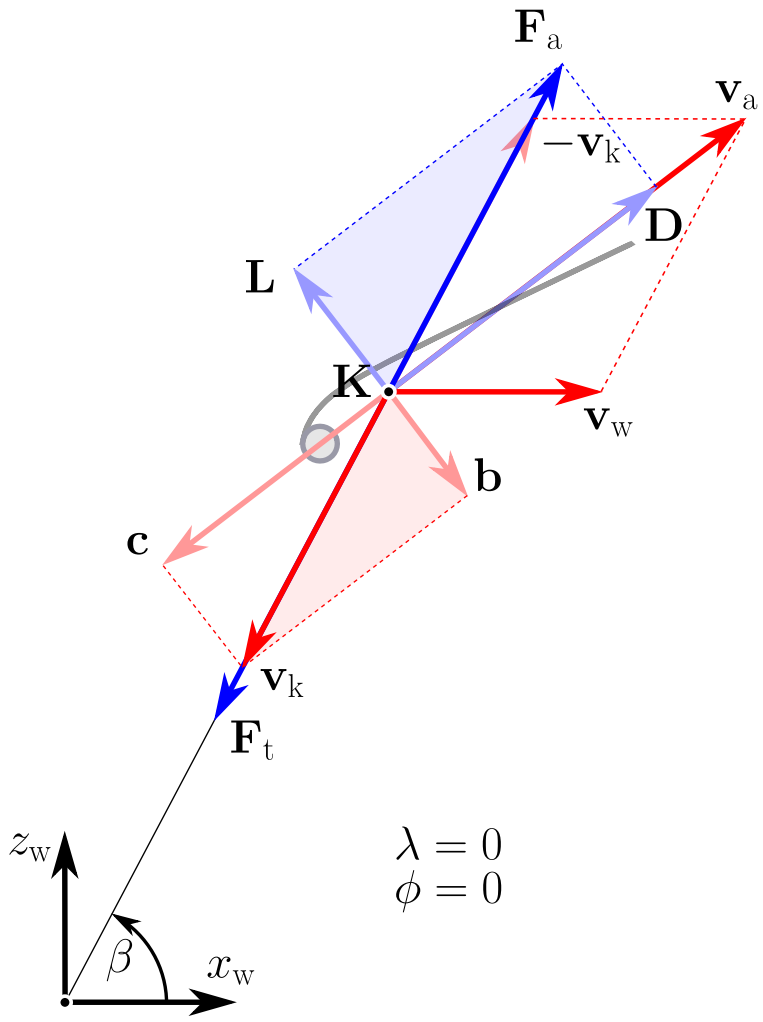
Instantaneous mechanical power

$$\frac{P}{P_\mathrm{w}S} = C_\mathrm{L}\sqrt{1+\frac{1}{E^2}}\left(1+E^2\right)f\left(\cos\beta\cos\phi - f\right)^2$$



Reel-in state (soft-wing kite)

Representative reel-in state defined by E and f



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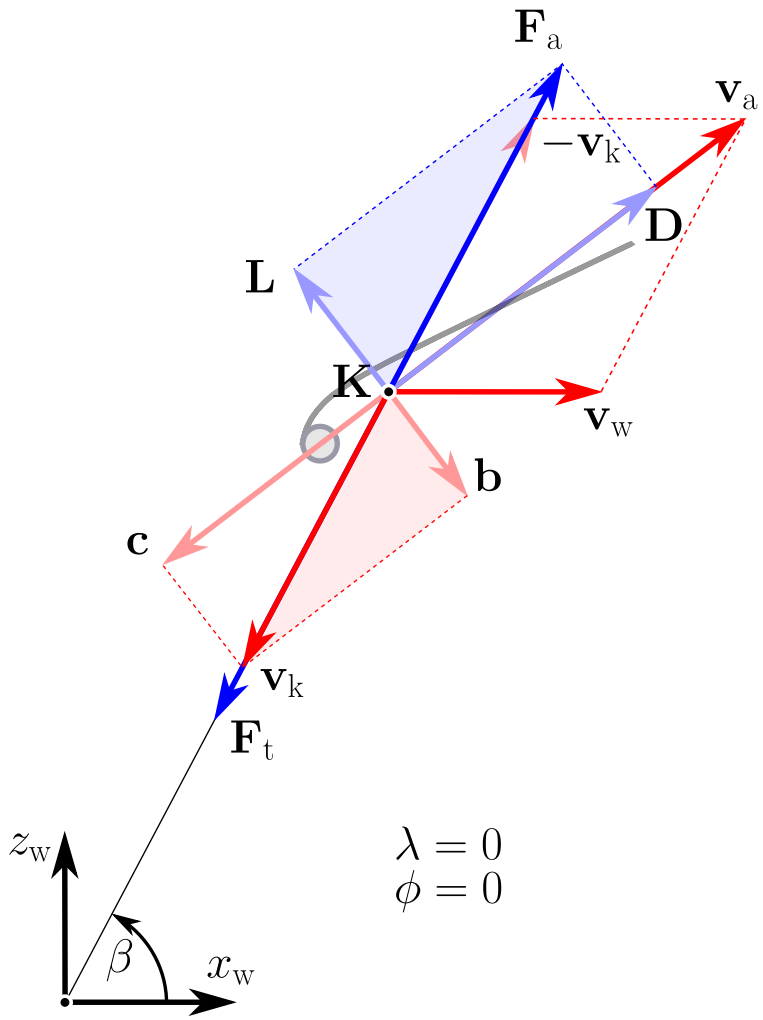
Representative reel-in state defined by E and f

- β is a dependent variable



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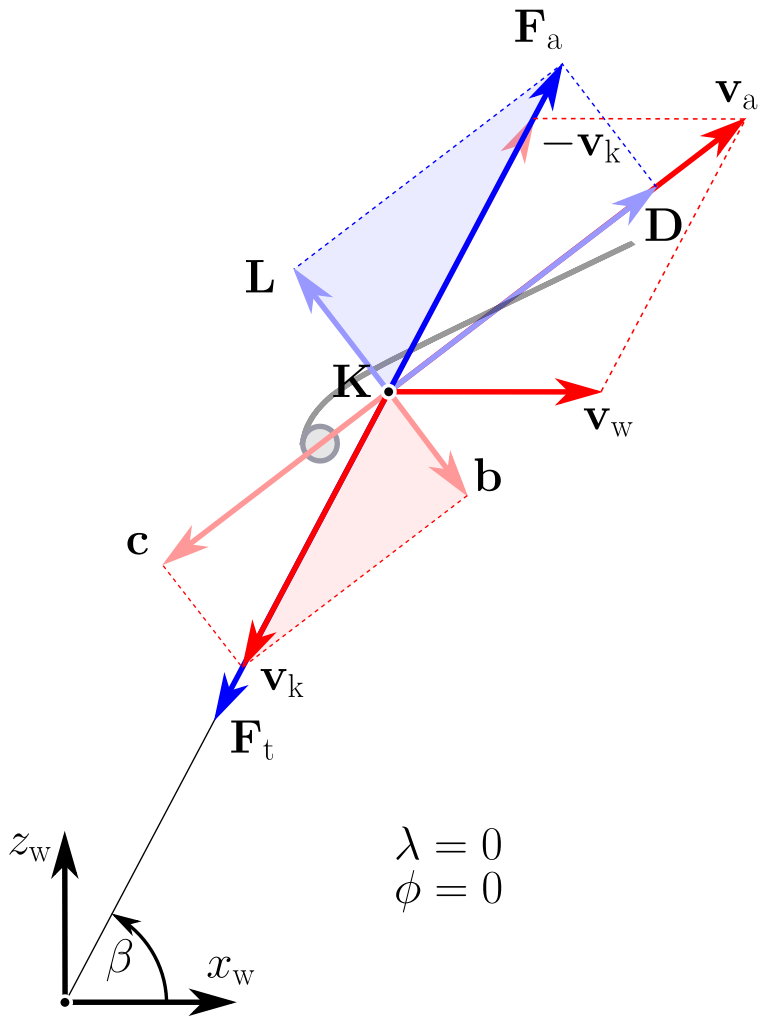
$$\frac{v_\mathrm{a}}{v_\mathrm{w}} == \frac{\sqrt{1+E^2\left(1-f^2\right)}-f}{\sqrt{1+E^2}}$$



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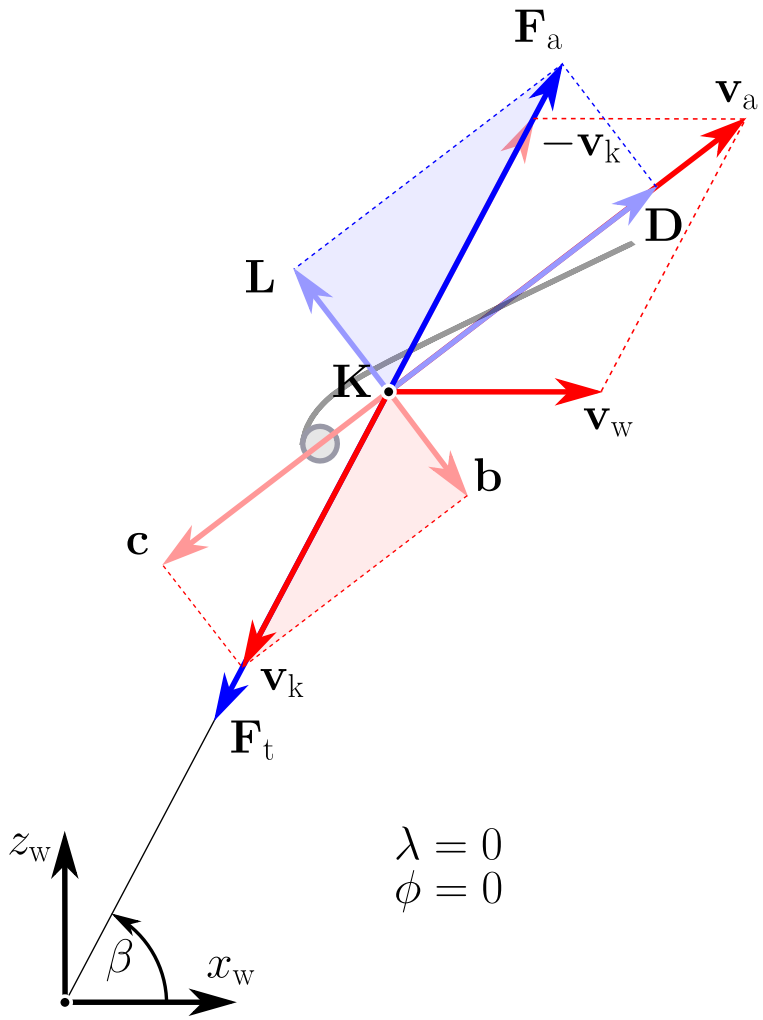

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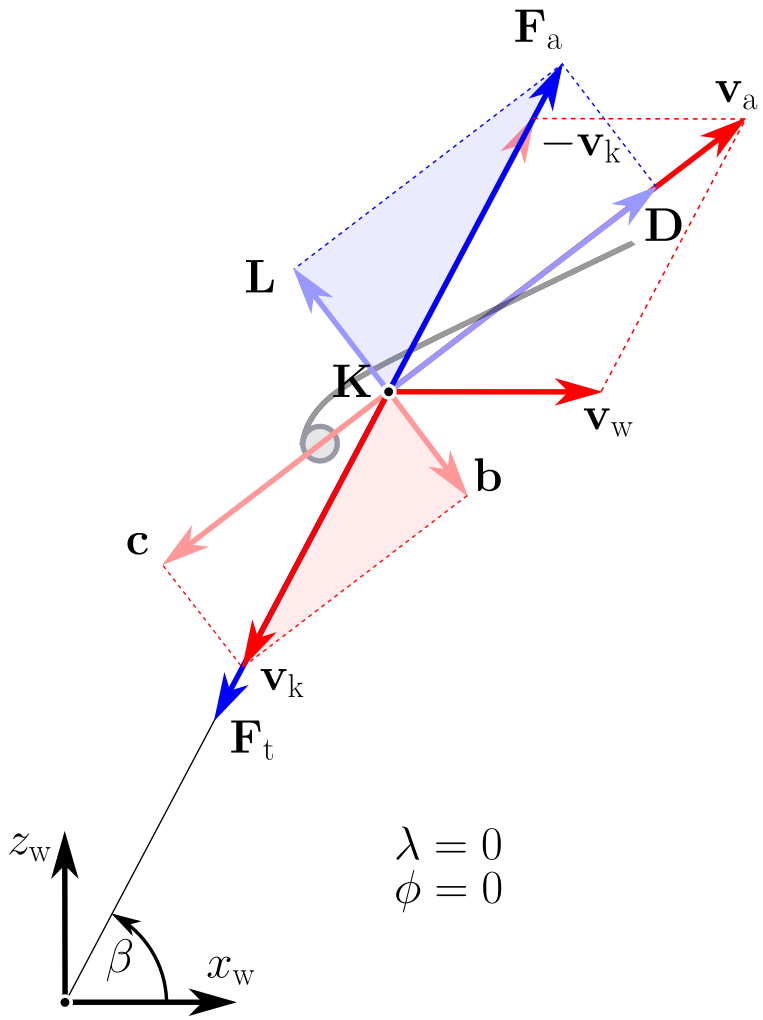
$$\frac{P}{P_\mathrm{w}S} = C_\mathrm{L}\frac{f\left[\sqrt{1+E^2(1-f^2)}-f\right]^2}{E\sqrt{1+E^2}}$$



Reel-in state (fixed-wing kite)

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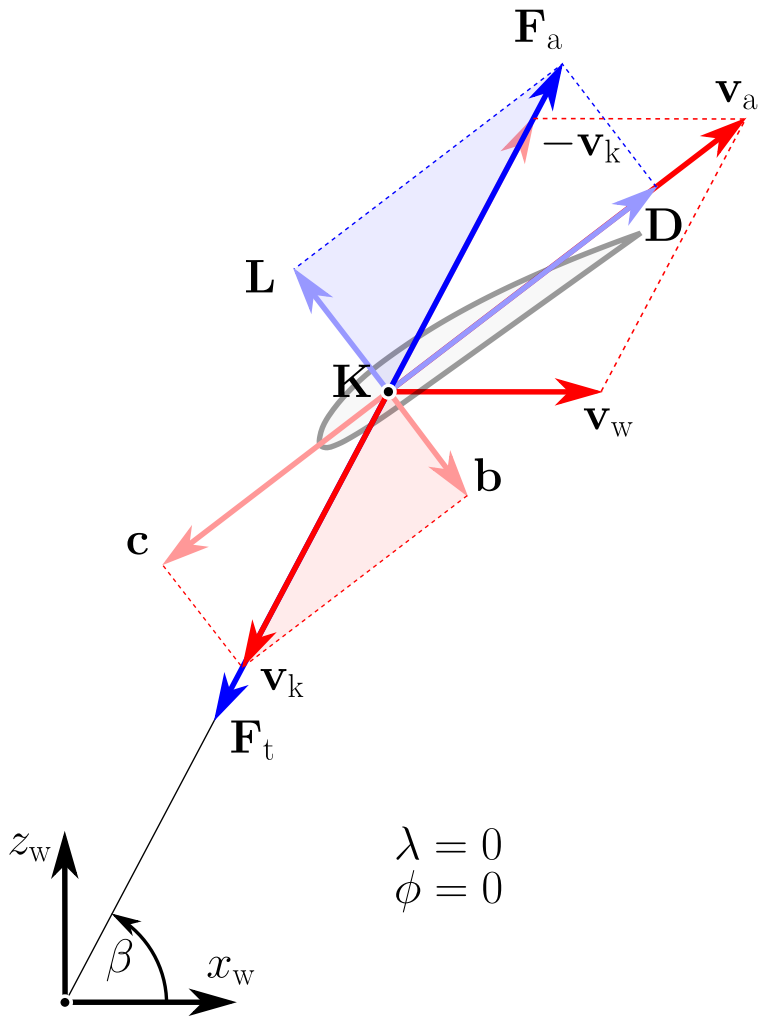
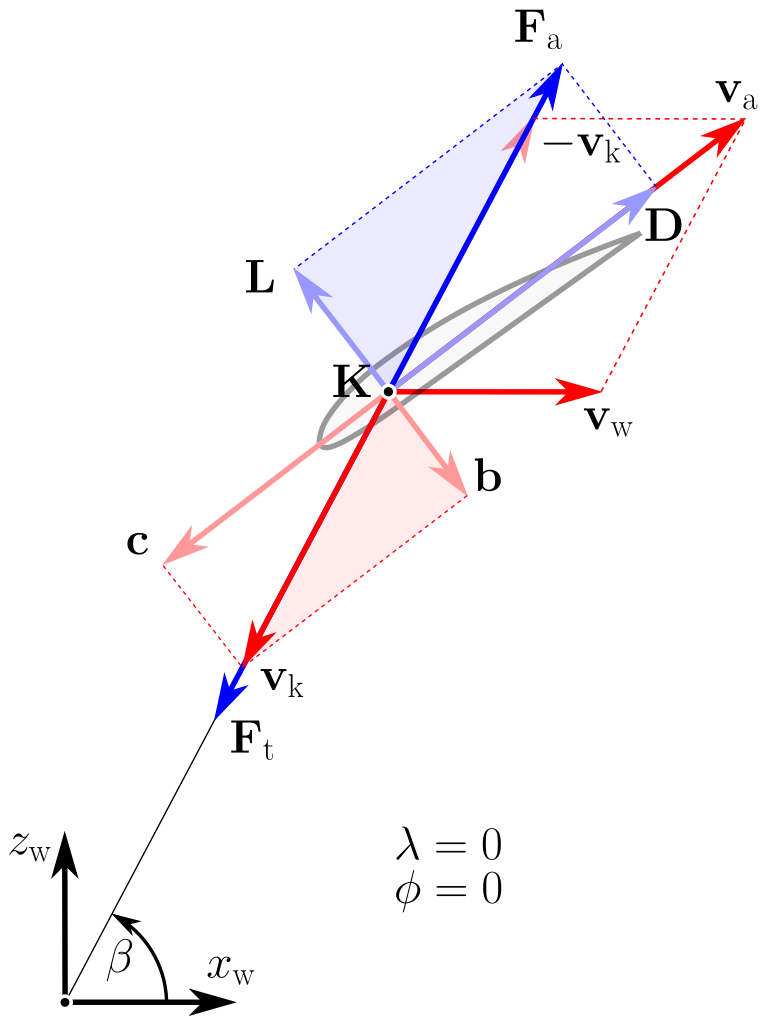


Reel-in state (fixed-wing kite)

Representative reel-in state defined by β and f

- E is a dependent variable



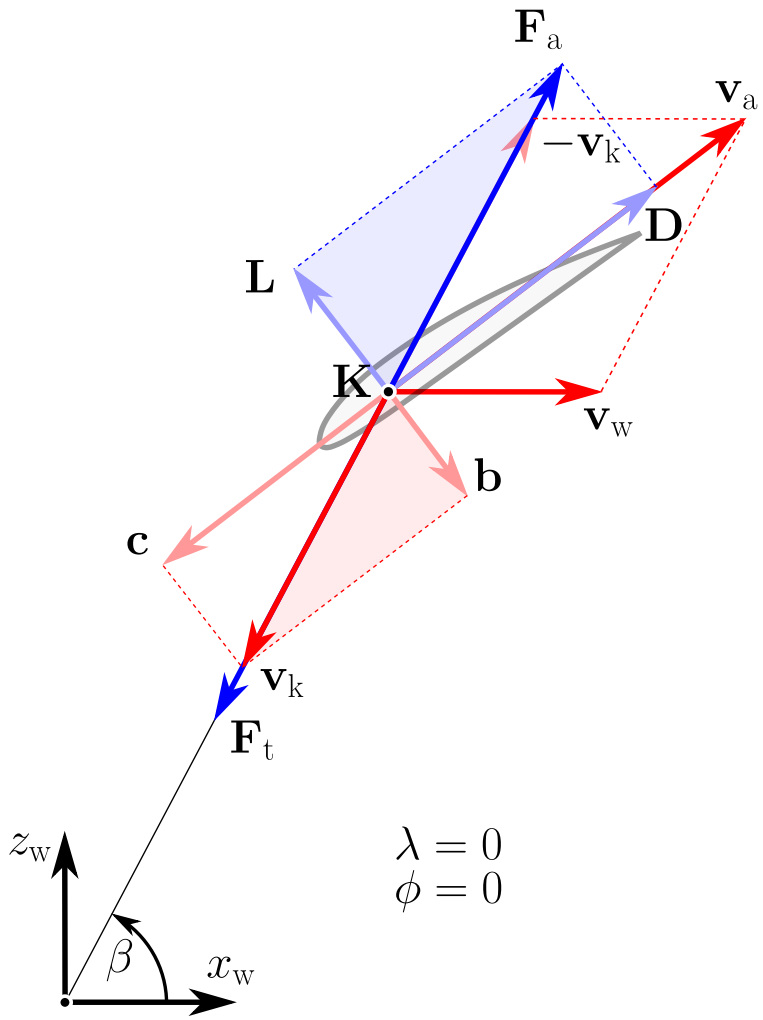
Reel-in state (fixed-wing kite)

Representative reel-in state defined by β and f

- E is a dependent variable

Apparent wind speed

$$\frac{v_\mathrm{a}}{v_\mathrm{w}} == \sqrt{1 - 2f\cos\beta + f^2}$$



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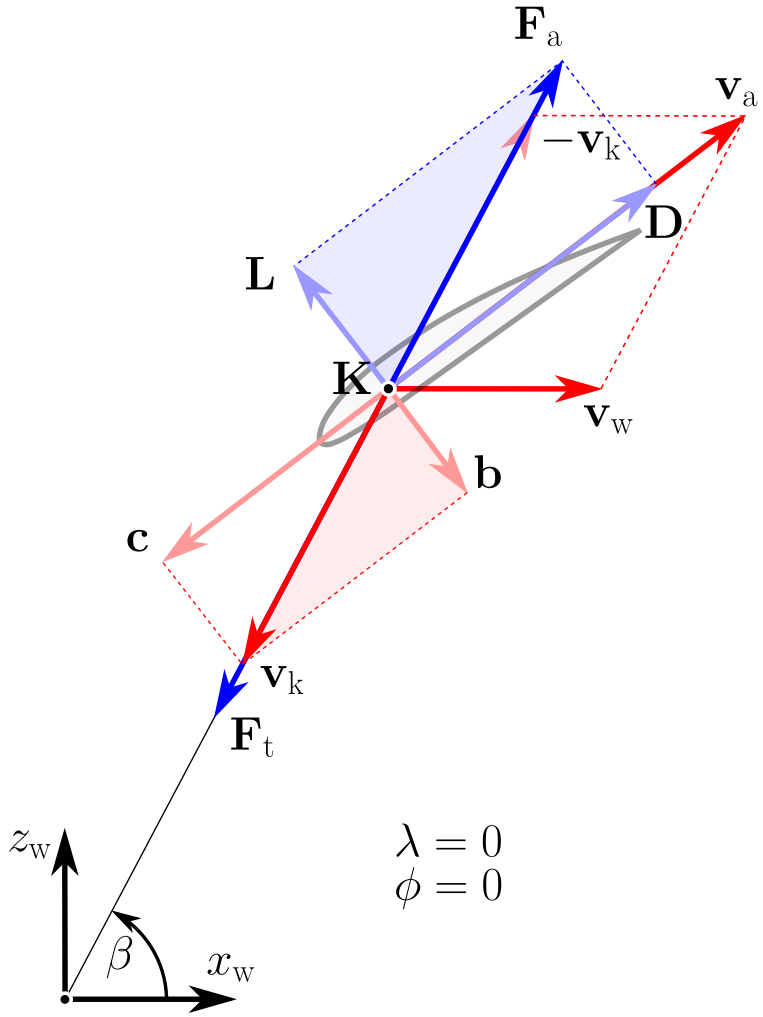

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Instantaneous mechanical power

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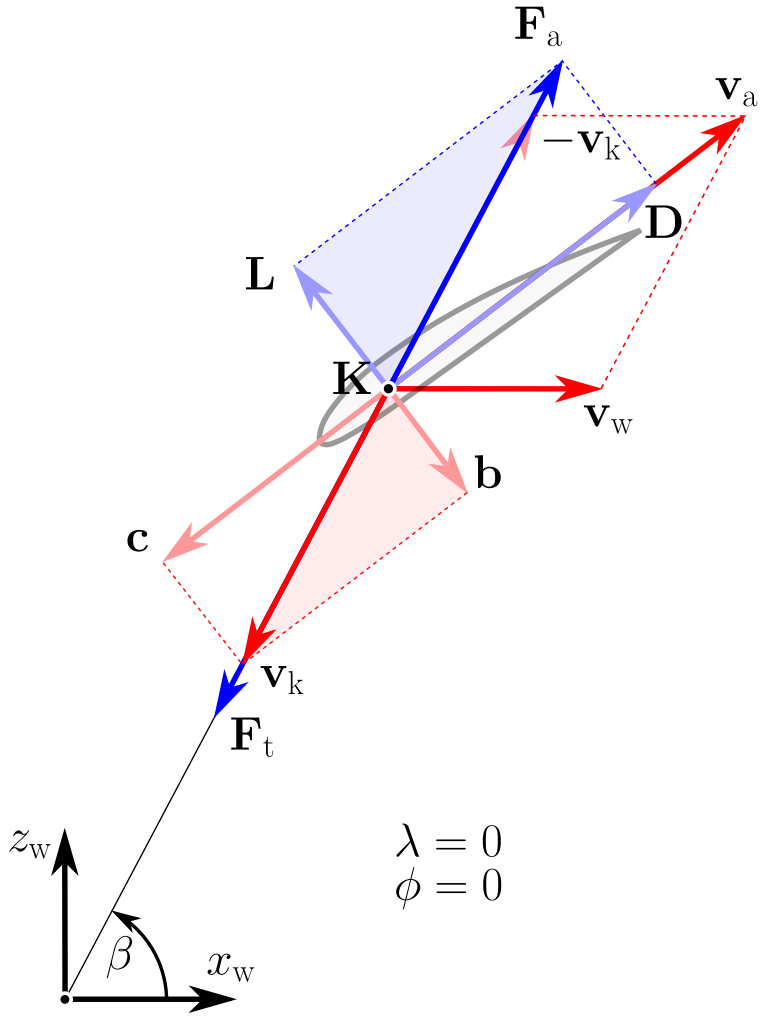

Further reading

Energy harvesting with kites is described in much detail in a draft chapter of the emerging course reader.

The accompanying Python code to compute the powercurve and operational data is available from a GitHub repository.

The powercurve and operational data is computed for the system described in this book chapter. Figure 23.15 in this chapter shows the experimentally derived powercurve.

Expanding the theory

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- Account for a **two-stage depowering strategy** during reel-out in wind speed regime 3. The continuous increase of the reel-out elevation angle (stage 1) is already coded but commented out. Stage 2, which is currently coded and used, would be an active depowering of the kite by changing its aerodynamic properties.

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- Account for **gravity and a non-zero mass of the kite**, by iteratively solving the quasi-steady force equilibrium equilibrium. The approach is explained in Vlugt et al. (2019).

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- Account for **gravity and a non-zero mass of the kite**, by iteratively solving the quasi-steady force equilibrium equilibrium. The approach is explained in Vlugt et al. (2019).
- Remove the assumption of infinitely fast transition phases and account for a **numerically integrated flight path during the reel-in phase**. The approach is outlined in Section 14.2.4 “Simulating the reel-in phase” of Fechner and Schmehl (2013) and also explained in question 3 “Retraction of a kite with non-vanishing tangential motion” of this exam solution.

References

Fechner, U.: A methodology for the design of kite-power control systems, (2016)
Fechner, U., Schmehl, R.: Model-based efficiency analysis of wind power conversion by a pumping kite power system. In: Ahrens, U., Diehl, M., and Schmehl, R. (eds.) Airborne wind energy. pp. 249–269. Springer, Berlin Heidelberg (2 October 2013)
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Vlugt, R. van der, Bley, A., Schmehl, R., Noom, M.: Quasi-steady model of a pumping kite power system. Renewable Energy. 131, 83–99 (2019). https://doi.org/10.1016/j.renene.2018.07.023

Questions?



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