exercise session 6

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Wind Energy Systems, Summer-Semester 2018

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July 18, 2018

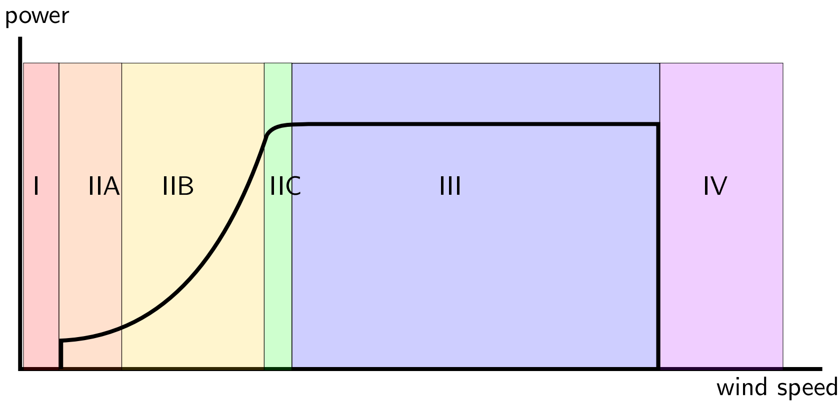
1. concept questions

2. homework

3. questions from you for me
   - a summary of lift and drag
   - a summary of the blade elment momentum method
   - tower dimension considerations

concept questions!

where is the rotor angular velocity constant?



a) I, IIA, IIC, III, IV

b) I, IIB, IIC, IV

c) I, IIB, IV

d) I, III, IV

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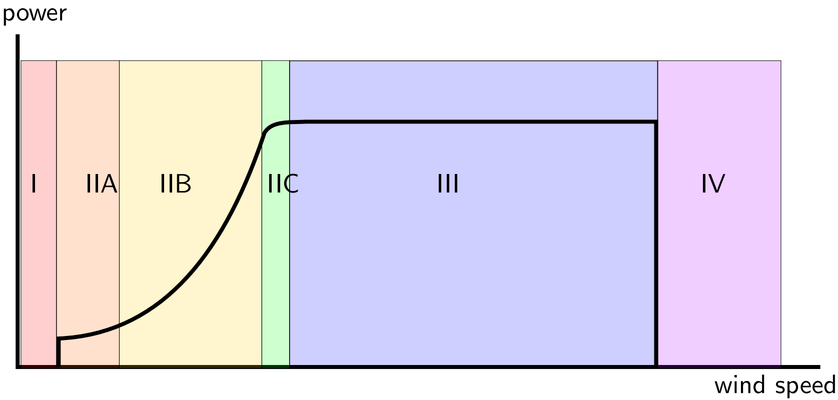

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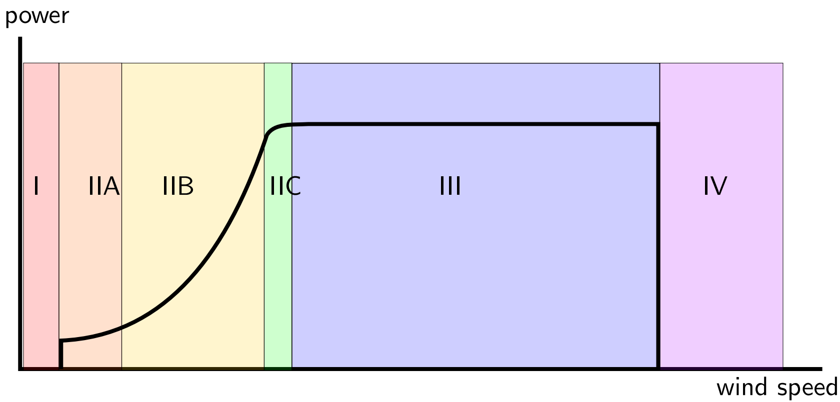
where is the blade pitch constant?



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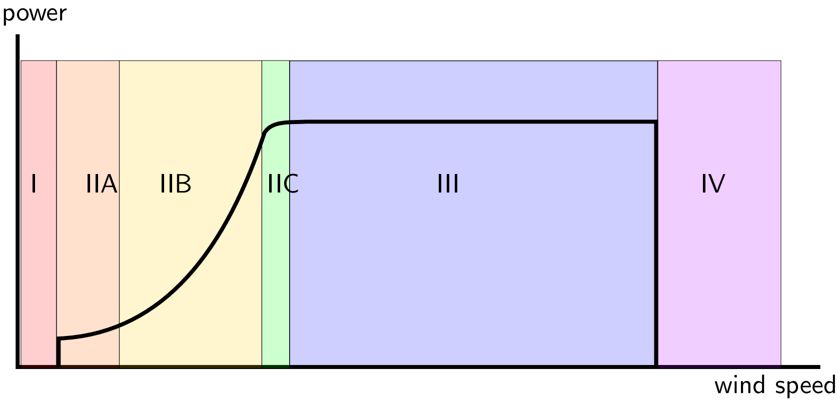

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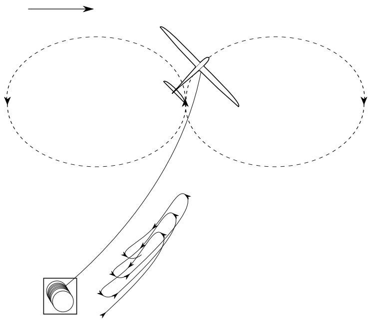
if there were NO TETHER DRAG and UNIFORM WIND FIELD...

where would the kite fly?



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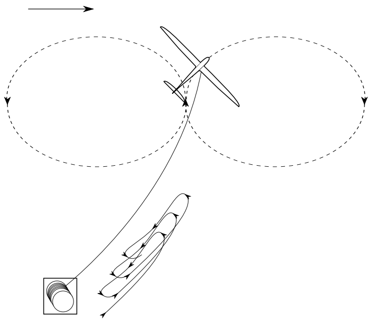

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vides an easy way for creating a large scale system with many medium sized wings stacked one above the other, see the left side of Fig. 1.5. Power could be generated via pumping or in other ways [6]. Care needs to be taken, however, with regard to the spacing between kites, whose airflows influence each other, so that the total power output does not increase linearly with the number of kites. In general, start-up of multiple wing systems is a delicate task, and reliability of the interconnected wings is a critical issue, so that no larger scale AWE system with multiple kites was built yet.

Lighter than Air Systems

While most airborne wind energy systems rely on aerodynamic lift in one form or the other in order to keep the system airborne, a few systems rely on aerostatic lift to stay aloft, i.e. the airborne part of the system is lighter than air. The advantage is that they can stay airborne in the absence of wind indefinitely, and without power consumption. On the other hand, they need a considerable volume to compensate the weight of the rest of the airborne system – this volume is typically filled with Helium. An interesting fact is that power generation comes along with significant tether tension and when the wind blows and power is produced, the tether force, which is partly directed in vertical direction, largely dominates the weight of any airborne wind energy system; thus, the advantages of lighter than air systems become obsolete when they do generate power.

Two of the lighter than air systems that have been realized in recent years, the systems by Magenn power and Altaeros Energies mentioned earlier, both use on-board power generation with the additional weight burden of the electrical generator. To the best of the author's knowledge no crosswind kite power systems exist in this class; their large volume constitutes a fundamental design limitation for achieving high lift-to-drag ratios.

1.4 Fundamental Physical Limits of Airborne Wind Energy

Let us in this section look in more detail at the physical foundations of airborne wind energy. We will derive a refined variant of Loyd's formula defined by Eq. (1.2) and prove that it is in fact an upper limit of the power that any flying wing can extract from the atmosphere. Let us start with a simple, but very fundamental observation that holds for any wind power extracting device. For this aim we do not look at the generated power, but instead at the power that the wind power system extracts from the atmosphere, i.e. the power that is removed from the wind field due to the presence of the device.

Lemma 1.1 (Power Extraction Formula). *Regard a constant wind with speed v_w. The total power P_{wind} that a flying wing extracts from this wind field is given by the*

product of v_w with the total aerodynamic force F_a that the wing experiences and the cosine of the angle γ between the direction of this force and the wind:

$$P_{wind} = v_w F_a \cos\gamma. \qquad (1.3)$$

An intuitive proof of this simple fact can be based on a thought experiment, as visualized in Fig. 1.4: we imagine that the airmass is at rest while the ground anchor point of the airborne wind energy device is mounted on a tractor that moves with a constant speed v_w against this airmass. The resistance of the airborne system causes a total aerodynamic force F_a that has a horizontal force component parallel to the tractor motion of size $F_a \cos\gamma$. This force is directed against the motion of the tractor, and the mechanical power that the tractor needs to maintain its speed is given by $v_w F_a \cos\gamma$. Extending the thought experiment such that not only the tractor, but the whole ground is moving against the air mass and pushed by a magic force, it is clear that the same power formula still holds for the work done by this magic force. The validity of the same formula for a fixed ground and a moving airmass is due to the equivalence of inertial frames; in reality, the magic force moves the airmass relatively to the ground, and is caused by the presence of high and low air pressure regions. □

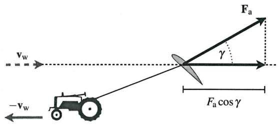

Fig. 1.4 Thought experiment from the proof of Lemma 1.1. A tractor moving at speed v_w and pulling a wing through air at rest performs a mechanical power of $v_w F_a \cos\gamma$. Conversely, if the air moves and the tractor is at rest, the same amount of power is extracted from the relative motion of the air with respect to the ground. It constitutes the power P_{wind} lost by the wind field due to the presence of the wing.

A simple conclusion from the lemma, that gives an upper bound on the usable power, is that no device can extract power from a constant wind field if it does not exert a horizontal force component against this wind. Most AWE devices have some losses, and most exert a force on the ground anchor point that is not parallel to the wind direction. In analogy to a similar expression in solar power, we might call the

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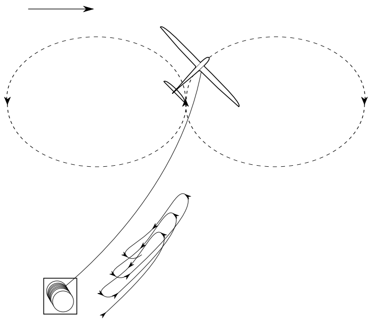

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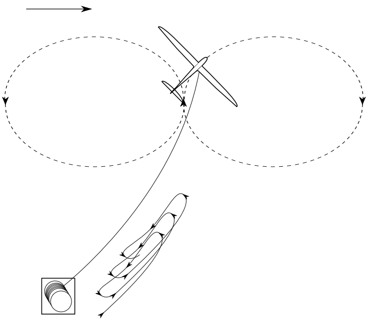

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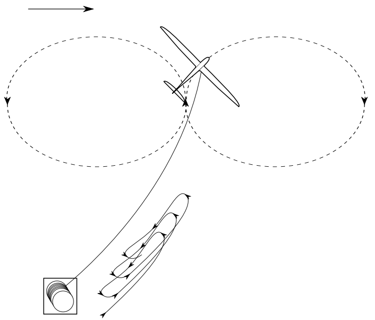

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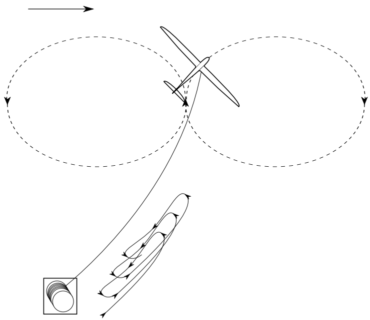

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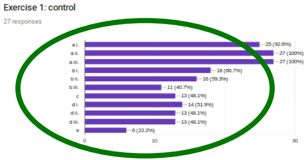

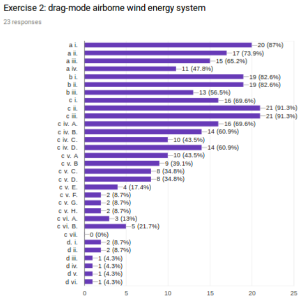

ex. 1	
b i	Rohit Gupta
b ii	Daniel von Kutzleben
b iii	Pankajkumar Kadam
c *	Irene Franzetti
d i	Hsin Chen
d ii	Paul Daum
d iii	Aksel Pettersen
e	Daniel Stürmer
a i	Mukund Wadhwa
a ii	Suwanto S
a iii	Sirin Alibas

* with some pseudo-code, please...

1 concept questions

2 homework

3 questions from you for me

- a summary of lift and drag
- a summary of the blade elment momentum method
- tower dimension considerations

a summary of lift and drag

	lift	drag
coefficients	c_ℓ (2D) and C_L (3D)	c_d (2D) and C_D (3D)
explanations	circulation of flow or Bernoulli	pressure differences around bluff bodies, skin friction, three-dimensional 'escaped flow' (induction), ...
direction	perpendicular to $\boldsymbol{u}_\mathrm{a}$ and span	parallel to $\boldsymbol{u}_\mathrm{a}$
α trend	roughly sinusoidal (linear for small α)	roughly parabolic

what do you want to talk about?

a summary of BEM

blade element expression decompose the forces experienced by rotor annuli into ~~radial~~, normal, and tangential direction.

=

momentum expression rate of change of axial and angular momentum

goal: find the wind velocity (with induction!)

main assumptions :

flow through annuli: in steady equilibrium, uniform in each annulii, and in independent streamtubes

normal direction aligned to wind axis

force distributed uniformly over each annuli

radial components negligible $\rightarrow$ lightly loaded rotor.

tower dimension considerations

main constraints:

bending stress less than material yield stress (with safety factor)

operational frequencies avoid tower (and other associated subsystem) natural frequency(ies)

design driver:

lifetime cost = materials + construction + transportation + operation + maintenance + decomissioning