ME-3A - SEM-3A - Master ENTECH, Master SGB, Master EFM

Rotor design and energy production forecasting over a year

Figure 1: Vestas V90-2.0 MW

Characteristics
Rated power : 2,000 kW/2,200 kW - rotor diameter 90m - nacelle Weight 70 t - rotor weight 41 t
cut-in wind speed : 4 m/s - cut-out wind speed : 25 m/s

Part I : Blade design and Power coefficient CP function of the tip speed ratio λ_R

Question I.1 Best lift-to-drag ratio

The aim is to size a 3 blades wind turbine thanks to a NACA0018 airfoil. Values of aerodynamics coefficients C_L and C_D are given for 69 angles of attack (α) from 0° to 180° (files CL-NACA18.txt and CD-NACA18.txt).
Problem solving is to be done with classic spreadsheet.

1. Plot curves of CL, CD and lift-to-drag ratio (LDR) CL/CD as a function of the angle of attack, for a Reynolds number of Re=2.10^6. Adapt the graph to regions of interest (0° - 25°).
2. The NACA0018 is not a laminar foil and consequently no laminar bucket exists on the CD or CL/CD curves. Give the values of $alpha_{stall}$, $alpha_{max}$ and $alpha_{deepstall}$ from the previous curves, the knowledge gained in aerodynamic lecture and from figure 3 below.
3. Determine the angle of best lift-to-drag ratio (LDR) which will be used for the design.
4. Note values of CL, CD and CL/CD for this angle value.

Question I.2 Chord and rotor surface determination

The main objective is to plot the blade shape and to illustrate the strong decrease of the total blade surface of a rotor as its design tip speed ratio λ_R increases. To do that, a loop from λ_R varying from 1 to 10 is proposed.

5. The blade root is the beginning of the aerodynamically active region of the blade at hub. In this study, the blade junction to hub will not be considered. Though the blade root radius will be taken equal to the hub radius R_h=0.05*R.
   The span of each blade is divided into 19 slices. From now on, we will use the dimensionless radius $r_d = \frac{r}{R}$. Calculate r_{di} for each center of two consecutive slices i.
6. For λ_R varying from 1 to 10, create a table of values as following:
   r_{di}, $\lambda = r_{di}\,\lambda_R$, β_i (flow angle), α_i (flow incidence), β_{pi} (pitch angle), Cl_i, Cd_i, $c_i=C_i/R$ (dimensionless chord), $i \in [1,19]$. The expressions of the various angles and quantities are provided in course.
7. Plot $c(r_d)$, λ_R from 1 to 10. Deform the figure to obtain an orthonormal view.
8. Comment values of the blade chord for slow turbines ($\boldsymbol{\lambda_R}$<3). Compare with the slow turbine on Fig 2 (using 32 flat plates blades). What is different? Compare the chord length at r=R with your results. What should be the $\boldsymbol{\lambda_R}$ of the turbine on Fig 2 ?

Figure 2: american wind turbine

9. Modern large wind turbine ($\boldsymbol{\lambda_R}$>6), as the Vestas 90 shown on Fig.1, are now considered: Comment the values of blade chord in the region close to the blade root. Does it correspond to the Vestas 90 blade shape? why?
10. In order to correct the blade root geometry, the angle of attack is increased from tip to root according to the following law:
    $$\boldsymbol{\alpha_i} = \boldsymbol{\alpha_{opt}} - 5\left(1 - \frac{1}{\sqrt{r_d}}\right). \qquad (1)$$
    Explain the purpose of this correction. Plot α_i (r_d). Is the angle of attack at blade root acceptable? Why
11. It is at first considered that the relation (1) is relevant. Pick up in the CL-CD-interpolation file the polynomial interpolations of CL(α) and CD (α) and use it to recalculate previous values of the blade chord with the modified angles (λ_R from 1 to 10 - orthonormal). Comment the results.
12. The coefficient 5 in the expression (1) is not a good choice (linked to question 10). Propose a better value (and explain) and recalculate the chord distribution (λ_R from 1 to 10 - orthonormal). plot blade chords for λ_R =8 in the 3 cases: original design and the two modified ones obtained in questions 11 and 12 (orthonormal). Draw qualitatively on this figure the junction to hub.
13. The last blade design is now considered (continuing to neglect the junction to hub). Calculate the percentage of the rotor disk occupied by the blades, S_B/S_D.
    - S_D is the rotor disk surface, equal to $S_D = \pi R^2$.

- S_B is the projection of the blades on the rotor plan.

Plot this percentage as a function of λ_R using a log/log scale and compare with the study of Hütter given in the lecture.

Question I.3 Power coefficient as a function λ_R and lift to drag ratio

14. Calculate C_T (rotor drag coefficient), C_M (rotor torque coefficient) and C_P (rotor power coefficient) as a function of λ_R.
15. To examine the effect of the foil lift to drag ratio (LDR) on the rotor performance, it is proposed to multiply $C_D(\alpha)$ by a r coefficient in order to simulate a better (r<1) or a less (r>1) LDR ($CL(\alpha)$ is unchanged). Give the relation between r, the original lift to drag ratio LDR_{org} or and the modified lift to drag ratio LDR_{mod}
16. Recalculate the $CP(\lambda_R)$ curve for different LDR_{mod} corresponding to typical aerodynamics applications (Fig. 4) and 2D foils from Sandia and Abbott (Fig. 5).

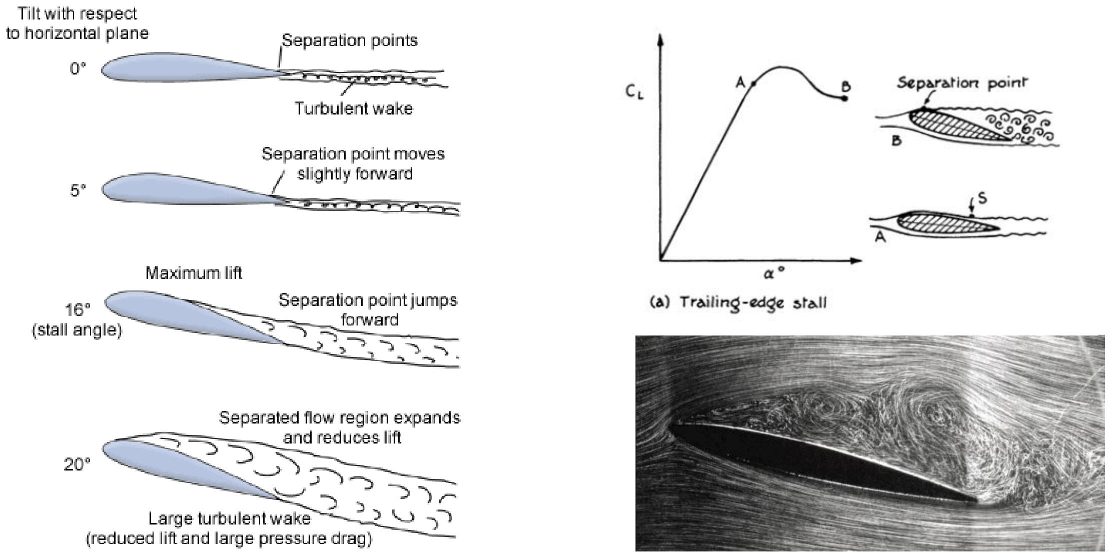


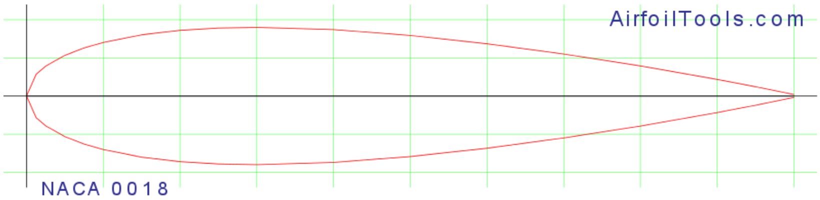
Figure 3: stall on an airfoil

			
Wing-suit LDR=3	Paragliding LDR=10	Hang-Glider LDR=15	Rigid hang-glider LDR=20

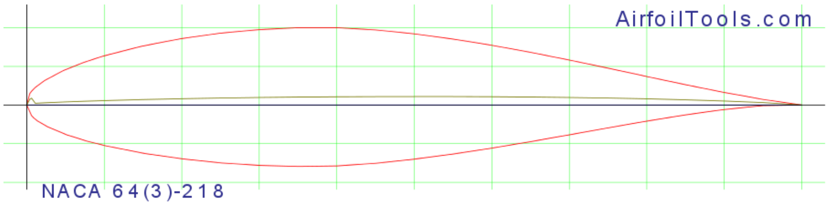
		
Airbus A320	Glider	Peformance glider

LDR=17	LDR=30	LDR=60

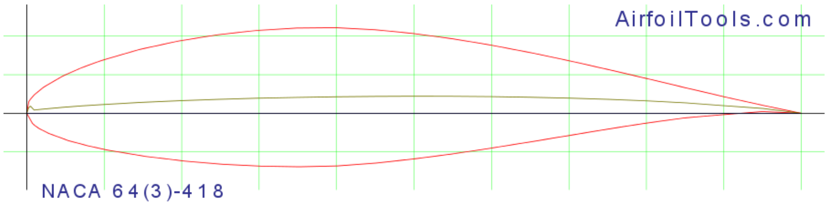
Figure 4: Typical lift to drag ratios



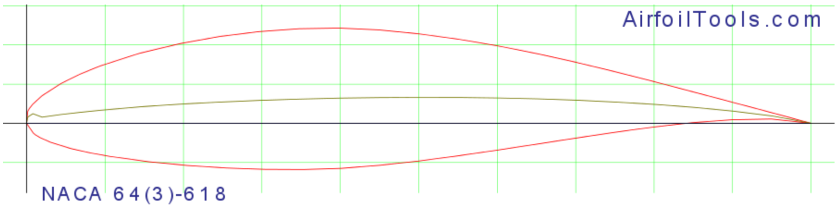
LDR = 76 (Re=2.10^6 – from SANDIA)



LDR = 100 (Re=3.10^6– from ABBOTT)



LDR = 130 (Re=3.10^6– from ABBOTT)



LDR = 150 (Re=3.10^6– from ABBOTT)

Figure 5: Typical lift to drag ratios obtained in laboratory on 2D foils from Abbott.

Part II: Energy production over-a-year forecasting

We aim at installing a same wind turbine in two sites characterized by different wind power density: an off shore site (k=2) with strong winds spread over a large range of velocities and an on shore site with moderate winds concentrated around the mean value (see table 1). For all calculations the air density ρ is considered equal to 1.2 Kg/m^3.

V_0 m/s	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
hours k=2	173	318	451	556	618	650	654	622	570	506	434	358	293	231	177	126	87	58	40	29	22	18	14
hours k=4	0	36	131	291	524	815	1056	1194	1130	874	546	262	116	29	0	0	0	0	0	0	0	0	0

Table 1: wind distributions on 2 sites

Question II.1 Wind potential, nominal velocity, rotor radius, power and rotation speed

(To be done for both sites k=2 and k=4)

1. Plot the wind speed distribution (h/year) versus velocity and calculate the percentage of windy hours.
2. Plot the wind energy per unit area and per year (kWh/m^2/year) versus velocity
3. Plot the cumulated wind energy per unit area and per year (kWh/m^2/year) versus velocity.
4. Using the preceding question, plot the energy production (kWh/m^2/year) of a wind turbine versus its nominal velocity, considering that for velocities greater than Vn, the rotor power is kept constant. The rotor power coefficient CP is taken equal to 1. Present also these curves in term of percentage of the maximum energy production.
5. The loading factor LF is the energy produced E divided by the energy that would be produced by a rotor working 24h/24 at its nominal velocity Vn (and power Pn). This energy is called E-Pn24. Plot E-Pn24 (kWh/m^2/year) and the loading factor LF versus Vn. Explain the maximum value of LF.
6. From curves obtained in question 4. and 5. propose a nominal velocity for the 2 sites knowing that a LF <0.2 is considered as a lower limit for on shore sites (all the more true for off shore sites). Explain clearly the tradeoff between the energy produced on one hand and the loading factor on the other hand.
7. We want to use the same turbine on the two sites. Table 2 gives its power coefficient as a function of the tip-speed-ratio .

λ_R	1	2	3	4	5	6	7	8	9	10	11	12
CP	0	0,004	0,056	0,174	0,304	0,4	0,44	0,424	0,36	0,258	0,127	-0,024

Table 2: Wind turbine power coefficient

We choose a turbine nominal power equal to a 2.5 MW on the site k=4. Calculate the corresponding rotor radius. Calculate the nominal power of this turbine on the site k=2. Calculate the nominal turbine rotation speed $\Omega_{turbine}$ (rpm) for the 2 sites.

Question II.2: Fixed or varying rotor velocity?

8. Table 2 gives power coefficient of the used wind turbine as a function of the tip-speed-ratio. Plot the curve.
9. Plot the power P(kW) as a function of the turbine rotation speed (rpm) for the following wind velocities (m/s): 4, 6, 8, 9, 10, 11.
10. Considering k=4, identify on the graph operating points in this two cases:

a. Steady rotation speed (direct coupling)
b. Varying rotation speed (indirect coupling)

Why is the variable speed more profitable? Does the minimal exploitable speed vary between both technologies?

11. Give examples of methods to keep a constant power Pn for velocities over Vn.

Question II.3: Energy production for indirect coupling

(to be done for Vn proposed in question 6 for the two sites)

The wind turbine works in indirect coupling. The output frequency is regulated to 50Hz by power electronics. No gearbox is used and the rotor and generator are on a same shaft. The cut-in and cut-out speeds are 4m/s and 25m/s.

12. Give in a table the energy produced over a year for each speed interval (MWh/year). Deduce the total production over a year (GWh/year) and the corresponding loading factor.
13. Give other estimations of the total production over a year (GWh/year) and of the loading factor using question 4. Check that these values are close to the formers. Explain the origin of the small differences.

Question II.4: Energy production for direct coupling

(to be done for Vn proposed in question 6 for the two sites)

The wind turbine works in direct coupling, through a gearbox and an asynchronous generator with two pole pairs.

14. The cut-out speed is 25m/s. Calculate the cut-in speed
15. Give in a table the energy produced over a year for each speed interval (MWh/year). To do that, use the CP-interpolation file. Deduce the total production over a year (GWh/year) and the corresponding loading factor.
16. Calculate the gearbox ratio: $GR=\Omega_{El\text{-}rotor}/\Omega_{turbine}$ where $\Omega_{El\text{-}rotor}$ is the rotation velocity of the rotor of the electric generator.

Question II.5: Discussion

17. Why the capacity factor for k=2 is strongly lower than the one for k=4?
18. Which coupling is the most profitable?
19. For a given site, how to increase the energy production of a wind turbine without modifying its loading factor? Is it conceivable in the present two cases k=2 and 4? Discuss.