POLITECNICO
MILANO 1863
DIPARTIMENO DI ENERGIA

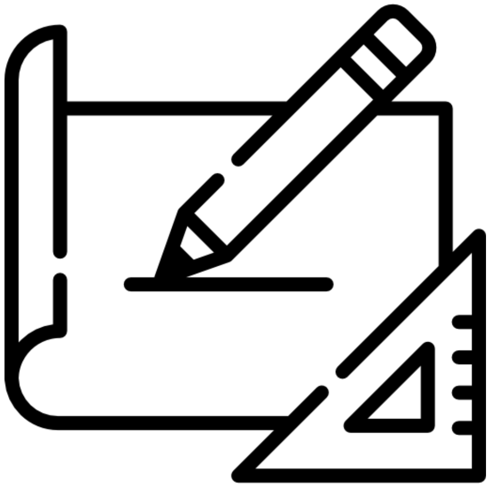
OFF-DESIGN PROCEDURE FOR HORIZONTAL AXIS WIND TURBINE

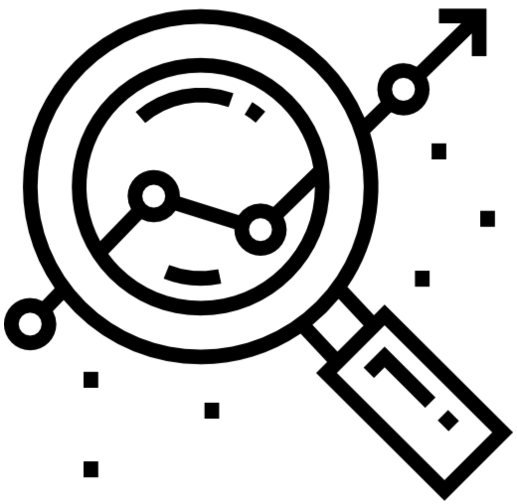
DESIGN OF FLUID MACHINES FOR
CLEAN POWER GENERATION 2017/2018

Alessandro Romei, alessandro.romei@polimi.it
Camilla Conti, camillacecilia.conti@polimi.it

DESIGN (INVERSE PROBLEM)

Design the geometry such that it generates the requested distribution of velocities (α, α'), which maximize the performance.





OFF-DESIGN (DIRECT PROBLEM)

Known the geometry (D, c, β_C , …), determine the corresponding distribution of the quantities of interest.

VARIABLE Ω + PITCH CONTROL

- **$V_{cut,\,in} < V < V_C$ (A – C)**

  $\dot{W}\uparrow,\ \beta_c = \text{const},$

  variable Ω: $C_P \cong C_{P,max} = C_{P,des}$

  at **C** $\Omega = \Omega_s,\quad C_P \cong C_{P,max}$

- **$V_C < V < V_r$ (C – D)**

  $\Omega = \Omega_s = \text{const}$

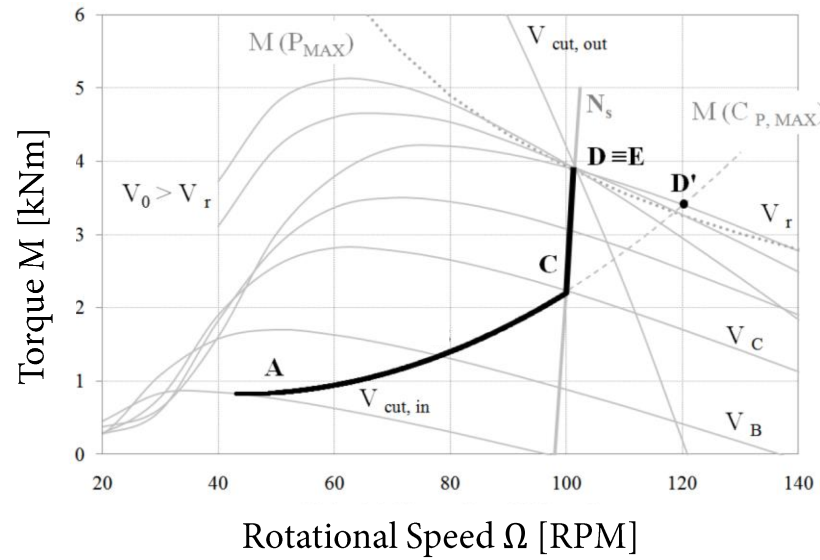
  $\dot{W}\uparrow\ \beta_c \uparrow$ and/or $\beta_c = \text{const}$ (check for stall)

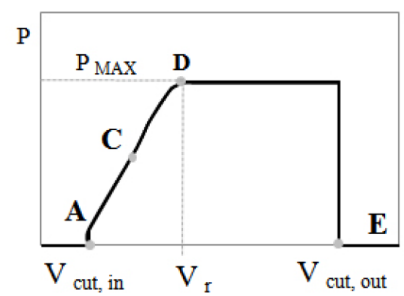
  at **D** $\dot{W} = \dot{W}_r,\quad V_D = V_r$

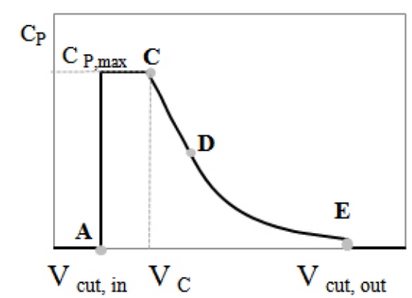
- **$V_r < V < V_{cut,\,off}$ (D – E)**

  $\Omega = \Omega_s = \text{const}$

  progressive $\beta_c \uparrow (C_P \downarrow)$ to keep $\dot{W} = \dot{W}_r$

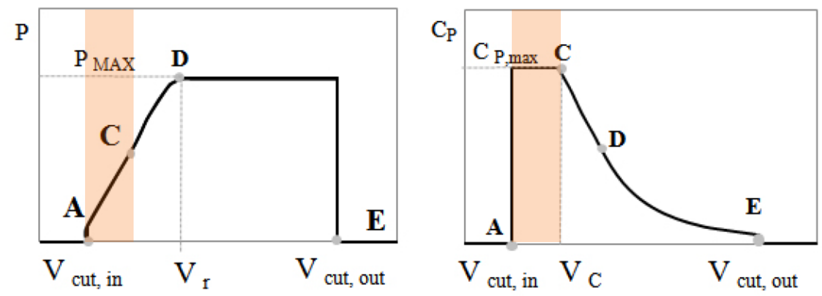






RANGE: $v_{cut,in} < v < v_C$

The idea is to change the rotational speed to keep $\lambda =$ const. (preserving the kinematic similarity).



For each $v \in [v_{cut,in}, v_C]$:

- Compute Ω from $\lambda = \lambda_{des}$
- Guess values for a, a' (1st guess → design distribution)

For each $R_j \in [R_{hub}, R_{tip}]$, given the geometry:

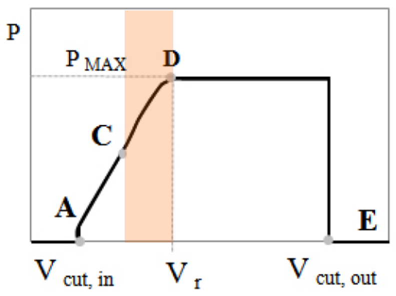
- Calculate W_∞, F
- Calculate β_∞, Re → C_L, C_D
- Calculate $\tilde{a}, \widetilde{a'}$ accounting for F and dD (from momentum eqs.)
- Convergence criterion on a, a'

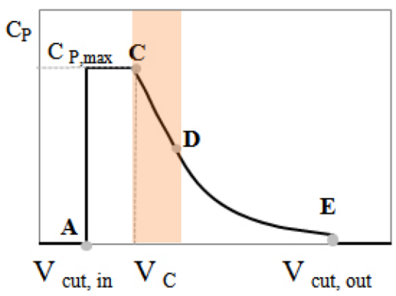
- Calculate $\dot{W}$, C_P (check $C_P \cong C_{P,max}$)

Actually, this algorithm is likely to be unstable in a close proximity of the point A (notice the jump in the CP diagram). In this region, the turbine has just begun to produce power and the CP computation is very sensitive to this value. Indeed, at low velocity, the turbine works in laminar regime and Reynolds effects heavily affect the turbine operations -> the task is to apply the algorithm to a couple of velocities close to the point C to assess the Reynolds effect.

RANGE: $v_C < v < v_r$

Rotational speed is fixed, sub-optimal condition leads to $C_P < C_{P,max}$. Pitch is controlled to avoid stalled blades (constraint: stalled blade < 20%).





For each $v \in [v_C, v_r]$:

- Pitch variation: $\Delta\beta_C = 0$
  - Guess values for a, a' (1st guess → design/previous distribution)

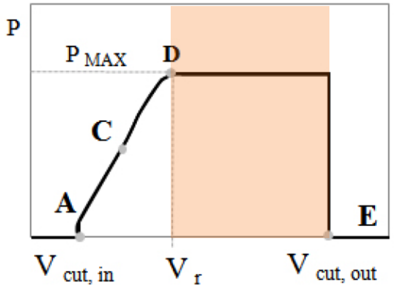
  For each $R_j \in [R_{hub}, R_{tip}]$, given the geometry and Ω:

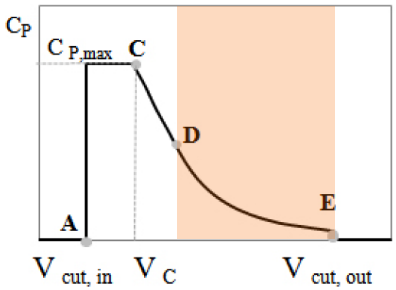
  - Calculate φ, W_∞, F
  - Calculate β_∞, Re → C_L, C_D
  - Calculate $\tilde{a}$, $\widetilde{a'}$ accounting for F and dD (from momentum eqs.)
  - Convergence criterion on a, a'
  - $\varepsilon = C_L/C_D < 0.95\ \varepsilon_{max}$? If so, local stall

  - Stalled blade < 20%? If not, increase $\Delta\beta_C$ and restart
- Calculate $\dot{W}$, C_P

RANGE: $v_r < v < v_{cut,out}$

Rotational speed is fixed, pitch is controlled to strike the target rated power (pitch to feather).





For each $v \in [v_r, v_{cut,out}]$:

- Pitch variation: $\Delta\beta_C = 0$
  - Guess values for a, a' (1st guess → design/previous distribution)

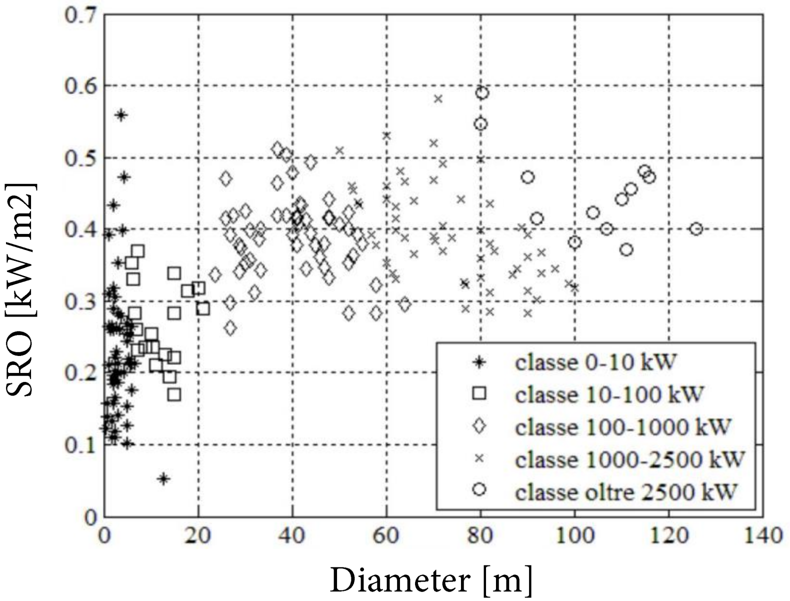
  For each $R_j \in [R_{hub}, R_{tip}]$, given the geometry and Ω:

  - Calculate φ, W_∞, F
  - Calculate β_∞, Re → C_L, C_D
  - Calculate $\tilde{a}, \widetilde{a'}$ accounting for F and dD (from momentum eqs.)
  - Convergence criterion on a, a'

  - Calculate $\dot{W}, C_P$
  - $|\dot{W} - \dot{W}_r| <$ toll ? If not, increase $\Delta\beta_C$ and restart

- $\mathbf{v_{cut,in}} = 3 - 3.5\ \mathrm{m/s}$
- $\mathbf{v_{cut,out}} = 25 - 28\ \mathrm{m/s}$ (on-shore) $30 - 35\ \mathrm{m/s}$ (off-shore)
- $\mathbf{v_C}$ limited by the tip peripheral velocity: $u_{tip,max} = \Omega_{max} R_{tip} = 70 \div 80\ \mathrm{m/s}$

$\mathbf{\dot{W}_r}$ can be decided by comparison with similar machines (statistical approach), e.g. SRO-diagram.



Similarly, the choice of $\mathbf{v_R}$ can be made by referring to a statistical database, e.g.

Annual mean wind speed, U_{ave} (m/s)	Optimum rated wind speed, U_{Ro} (m/s)	Ratio U_{Ro}/U_{ave}	Optimum rated power (kW)	Specific power, defined as rated power per unit swept area (kW/m^2)	Cost index, with cost of energy for a.m.w.s. of 7.5 m/s taken as100
7	12.4	1.77	1012	358	114
7.5	13.1	1.74	1187	420	100
8	13.7	1.72	1376	487	89
8.5	14.4	1.69	1579	558	80
9	15.0	1.67	1797	635	72

Tony Burton, Nick Jenkins, David Sharpe, Ervin Bossanyi, *"Wind Energy Handbook"*, John Wiley & Sons, 2001

$$\frac{v_R}{v_{ave}} \cong 1{,}7$$