UNIVERSITÀ DEGLI STUDI FIRENZE
DIEF
DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

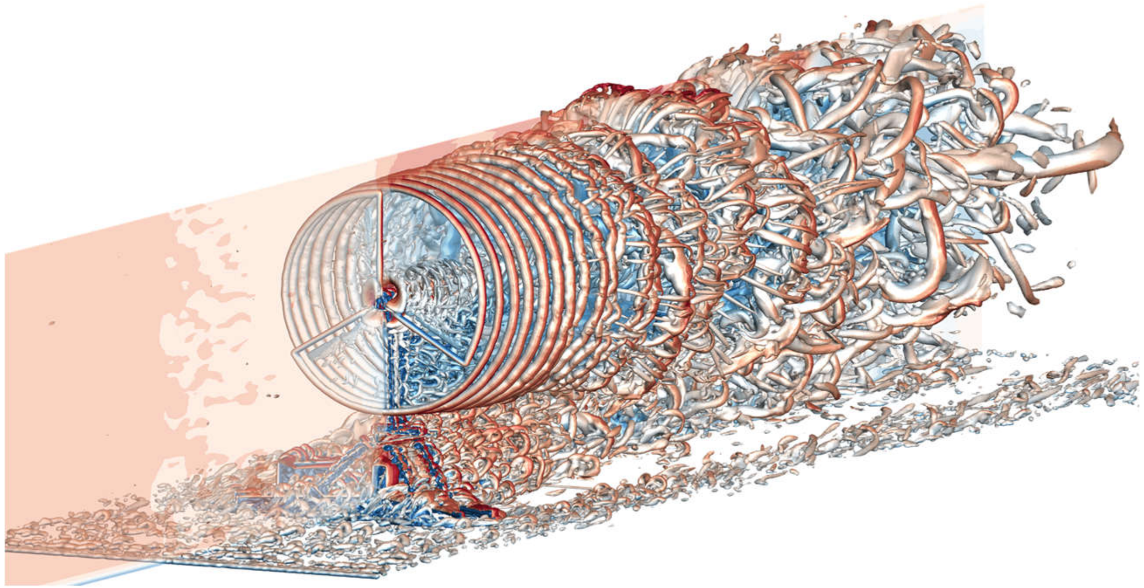
Wind turbine design & operation

Basics

Wind turbines **convert the kinetic energy in the flow into mechanical energy**

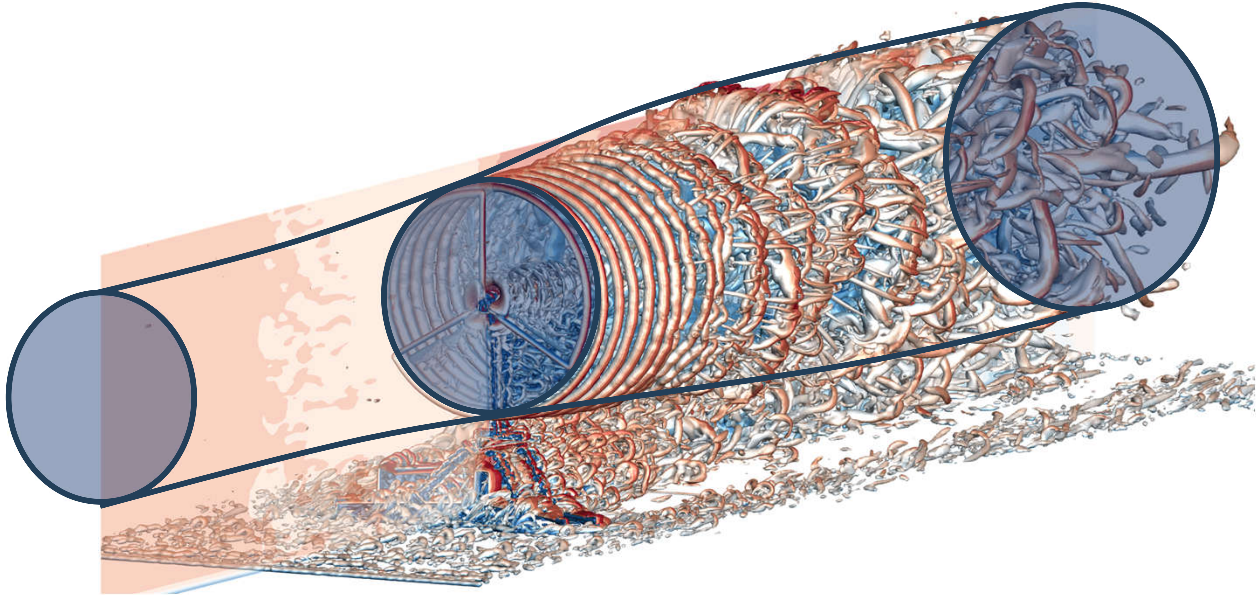
- ✓ We cannot stop the flow -> we cannot extract all the available energy -> **100% efficiency is impossible**
- ✓ **What is the theoretical maximum efficiency?** Betz first found an answer to this problem

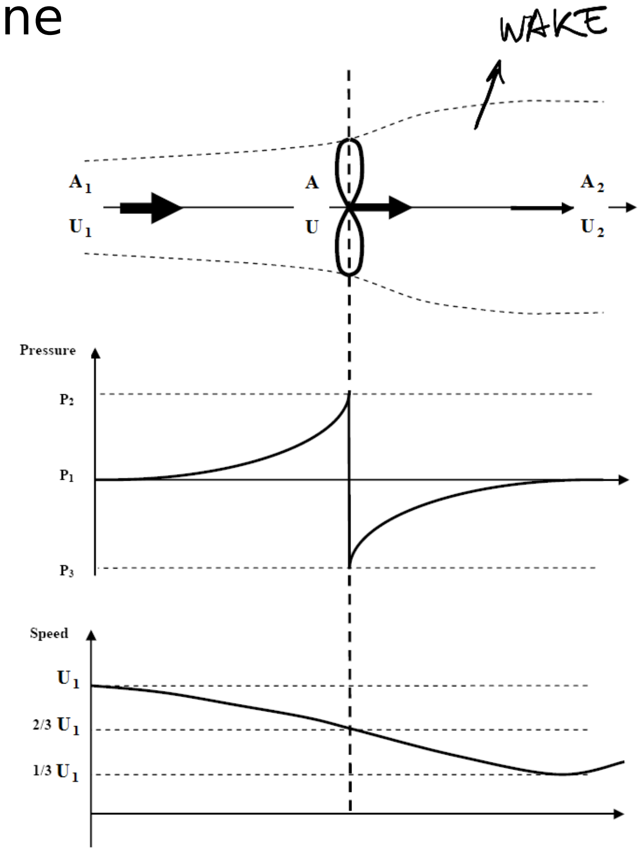
How do we design an efficient turbine?



Basics

Build a very simplified model of the flow around a wind turbine





Betz's law

Let's define the velocity at the rotor as U, the undisturbed velocity upwind as U_1 and the velocity downstream as U_2

Since the turbine is extracting energy from the flow: $U_2 > U_1$

Accordingly, the continuity equation (for incompressible flows) imposes an increase of the streamtube section, i.e.:

$$\boldsymbol{A_2 > A_1}$$

Control volume

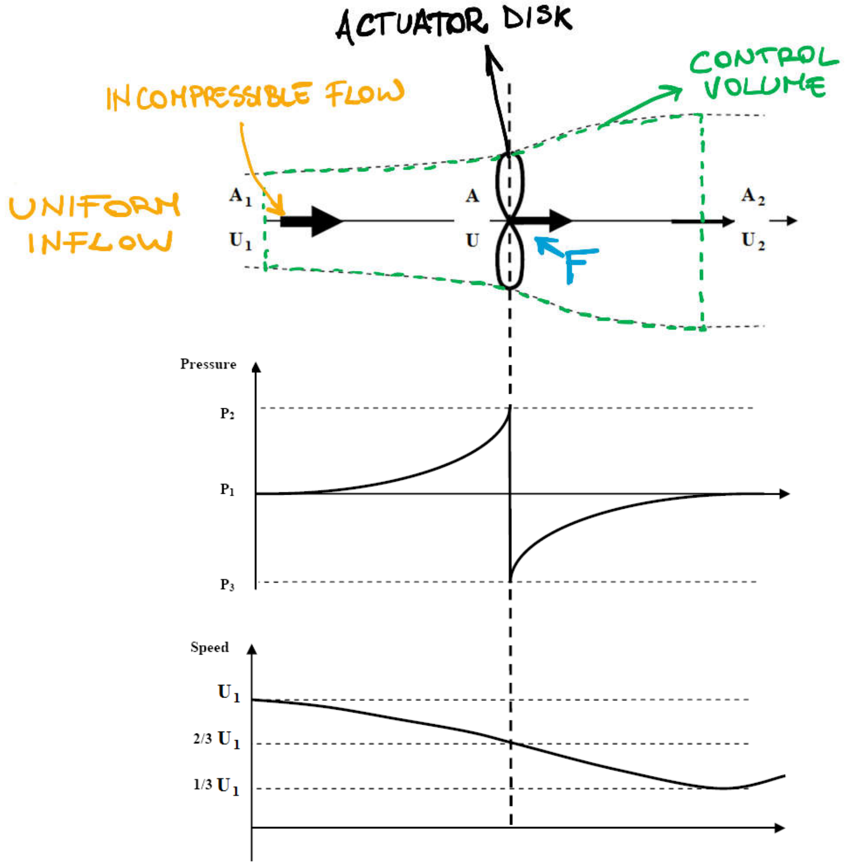
$$\dot{m} = \rho A_1 U_1 = \rho A U = \rho A_2 U_2 = \text{const}$$

The Euler theorem gives the exchanged force:

$$F = ma = m\frac{dU}{dt} = \dot{m}\Delta U = \rho A U (U_1 - U_2)$$

The power contained in the flow is then:

$$P = \frac{dE}{dt} = F\frac{dx}{dt} = FU \quad \text{->} \quad P = \rho A U^2 (U_1 - U_2)$$



Betz's law

Power can be also expressed as the variation of kinetic energy, i.e.:

$$P \cong \frac{\Delta E}{\Delta t} \cong \frac{\frac{1}{2}mU_1{}^2 - \frac{1}{2}mU_2{}^2}{\Delta t} = \frac{1}{2}\dot{m}\left(U_1{}^2 - U_2{}^2\right)$$

However: $\dot{m} = \rho AU$

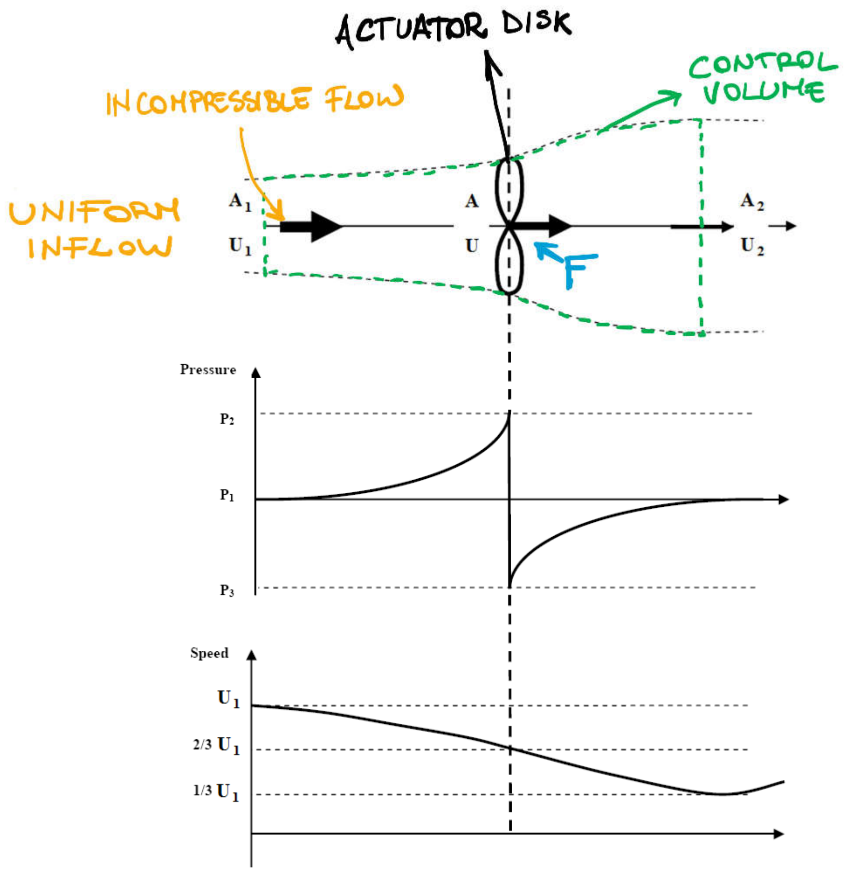
And thus: $P = \frac{1}{2}\rho AU(U_1^2 - U_2^2)$

We can now equate the two expressions for power:

$$P = \frac{1}{2}\rho AU(U_1^2 - U_2^2) = \rho AU^2(U_1 - U_2)$$

$$(U_1 - U_2)(U_1 + U_2)$$

And finally: $U = \frac{1}{2}(U_1 + U_2)$



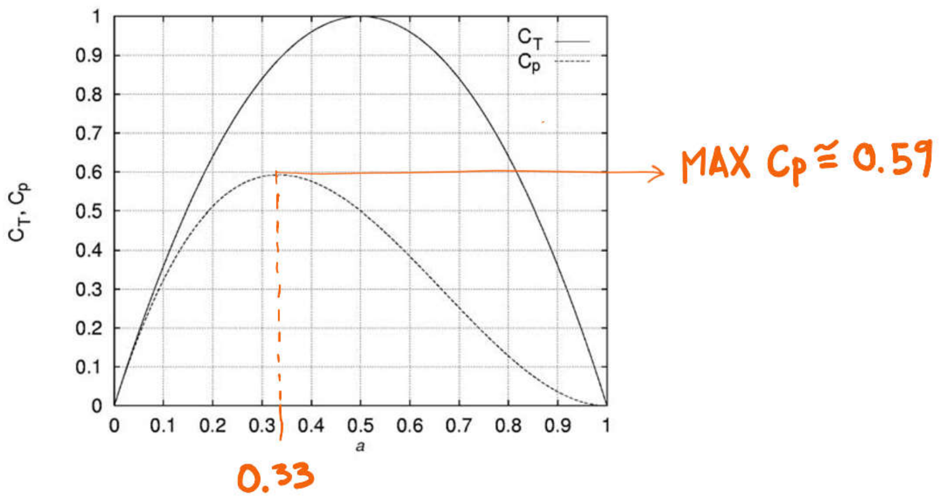
Betz's law

We can thus define the **axial induction factor:** $\boldsymbol{a = 1 - \frac{U}{U_1}}$ $\longrightarrow$ $U = U_1(1-a)$

$U_2 = (1-2a)U_1$

Introducing the expression for the induction factor into the expression of power: $P = \frac{1}{2}\rho A {U_1}^3 4a(1-a)^2$

The **power coefficient** is: $c_P = \frac{P_{extr}}{W} = \frac{\frac{1}{2}\rho A {U_1}^3 4a(1-a)^2}{\frac{1}{2}\rho A {U_1}^3} = \boldsymbol{4a(1-a)^2}$



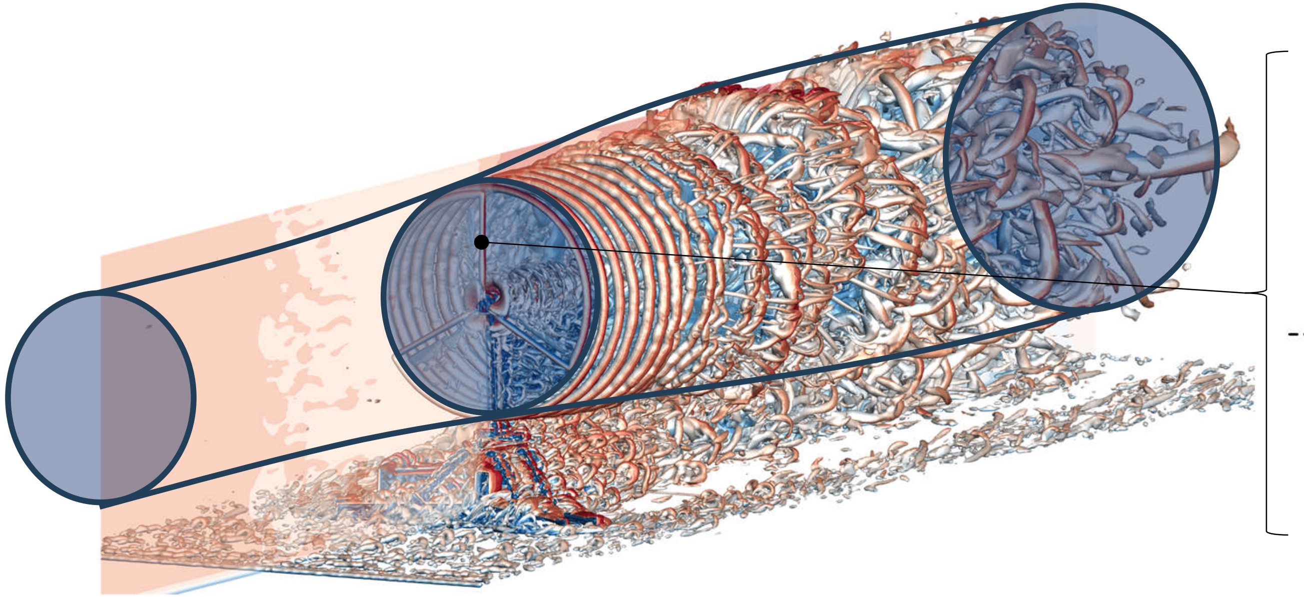
Betz's law - outcomes

- Maximum efficiency is achieved for an axial induction factor of 0.33
- We can correlate rotor forces and axial induction:

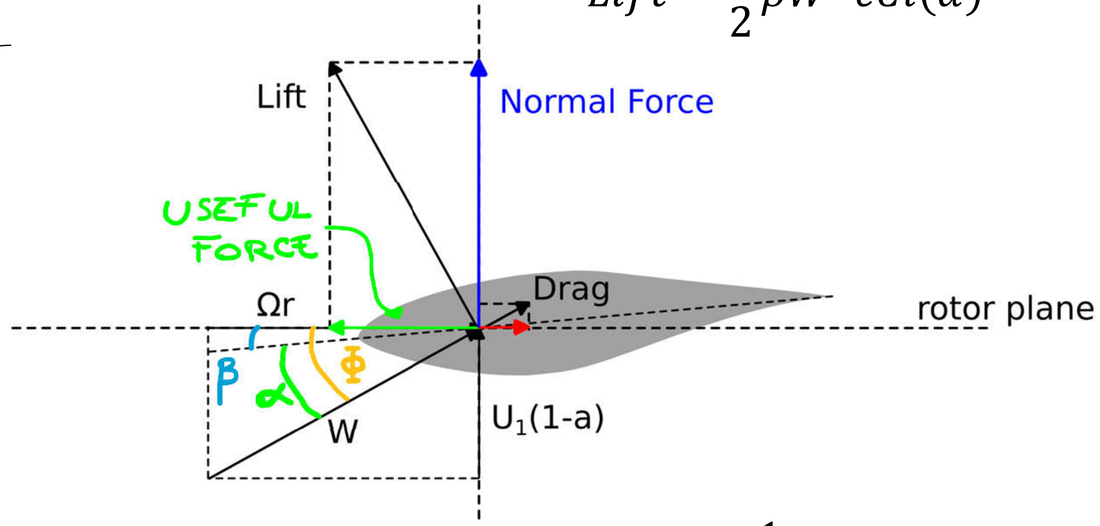
$$\mathrm{F} = \rho A U (U_1 - U_2) = \rho A U_1 (1-a)\big(U_1 - U_1(1-2a)\big) = \rho A U_1^2 2a(1-a)$$

Design Objective #1: Optimal rotor power is achived for a=1/3: $F = \frac{4}{9}\rho A U_1^2$

Rotor forces



$$Lift = \frac{1}{2}\rho W^2 c Cl(\alpha)$$



$$Drag = \frac{1}{2}\rho W^2 c Cd(\alpha)$$

Design Objective #2: Lift (useful force) to Drag (negative effect) ratio must be maximised

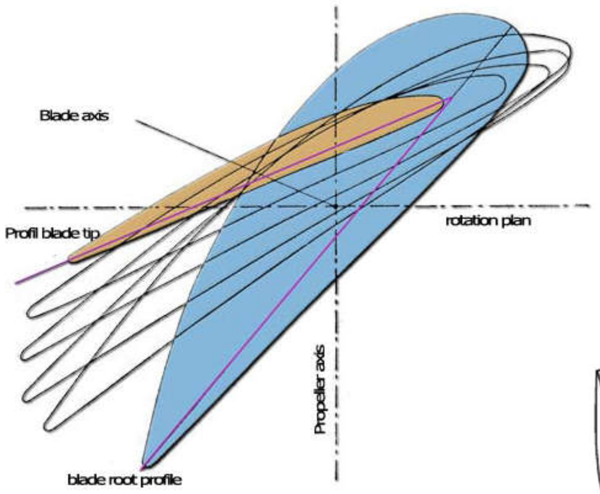
Wind turbine design

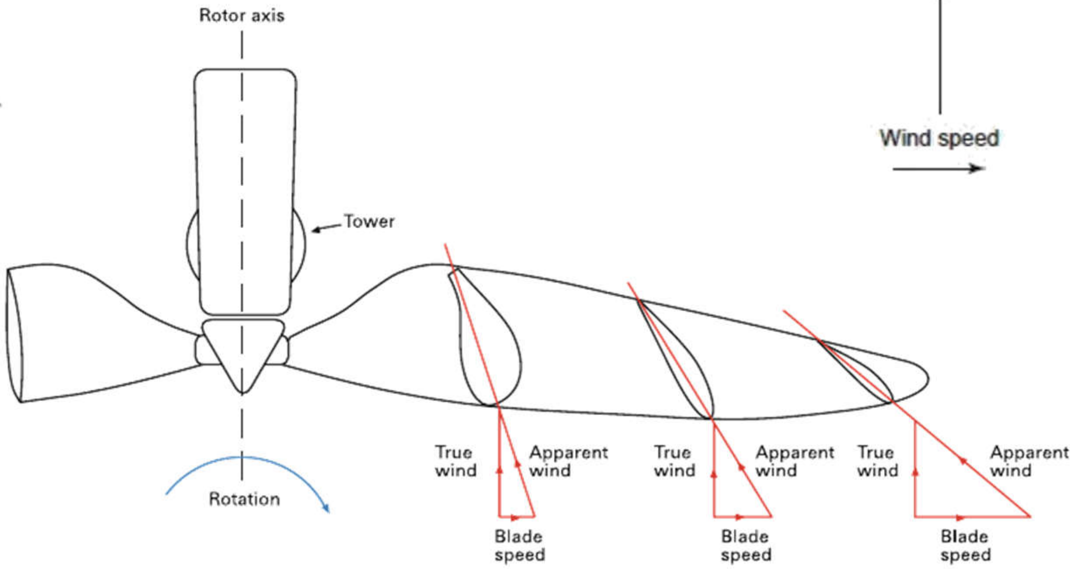
How to determine an optimal blade shape?

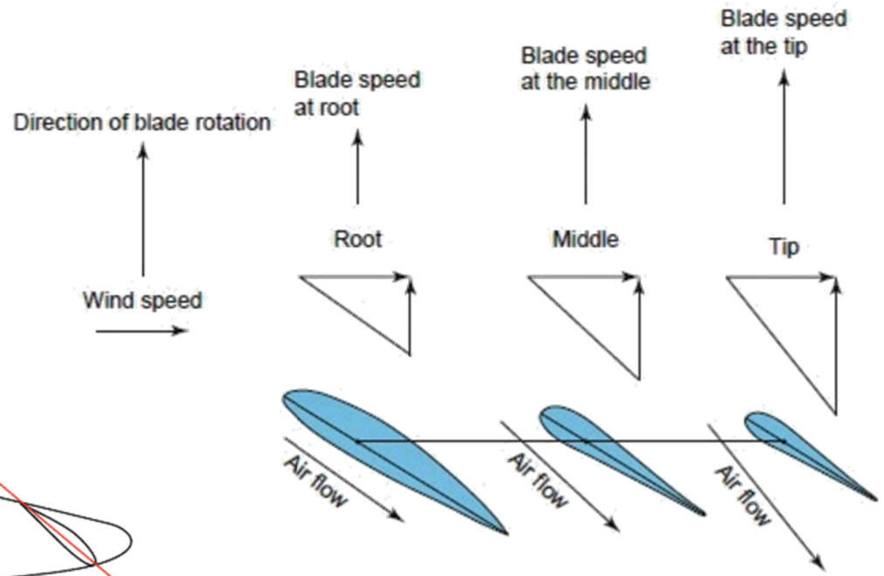
Blade shape

The peripheral speed, and then the incidence, is dependent on the radius

- ✓ the constructive angle at each section is modified to achieve the proper incidence angle: blades are “twisted”
- ✓ we must apply conservation of momentum for spanwise sections along the blade





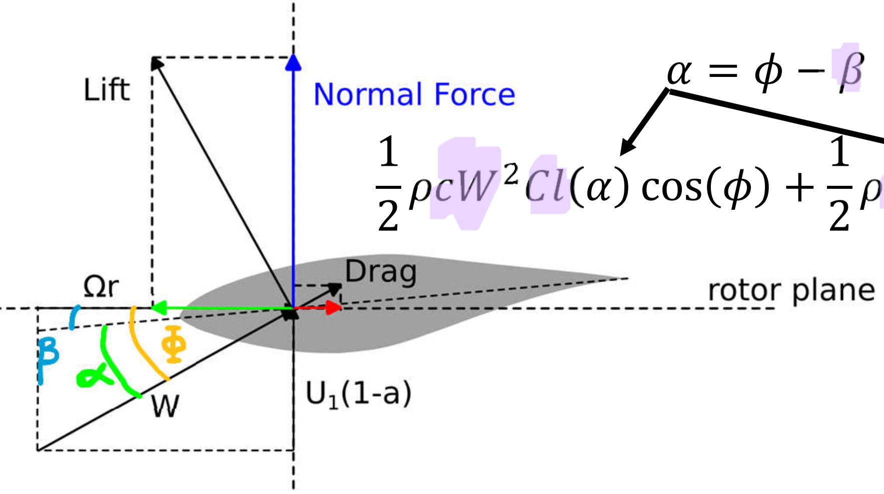


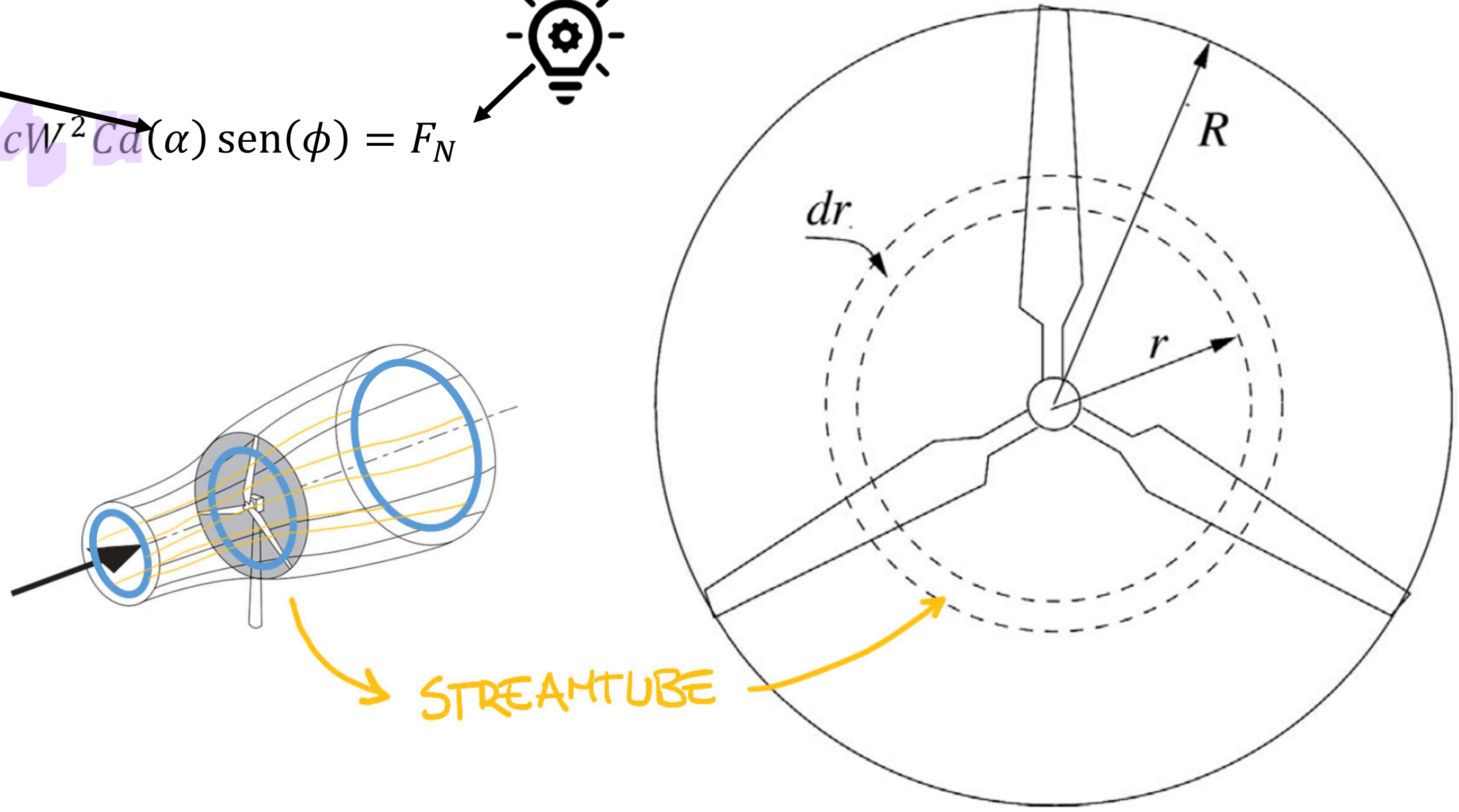
Relating rotor forces & blade shape

$$F_N = \rho A U_\infty^2 2a(1-a)$$

$$\alpha = \phi - \beta$$

$$\frac{1}{2}\rho c W^2 Cl(\alpha)\cos(\phi) + \frac{1}{2}\rho c W^2 Cd(\alpha)\,\mathrm{sen}(\phi) = F_N$$





We have related **axial indution** & **design variables**

- ✓ Cl and Cd depend on the section shape
- ✓ Chord and twist depend on how airfoils are stacked
- ✓ W depends on tip-speed ratio

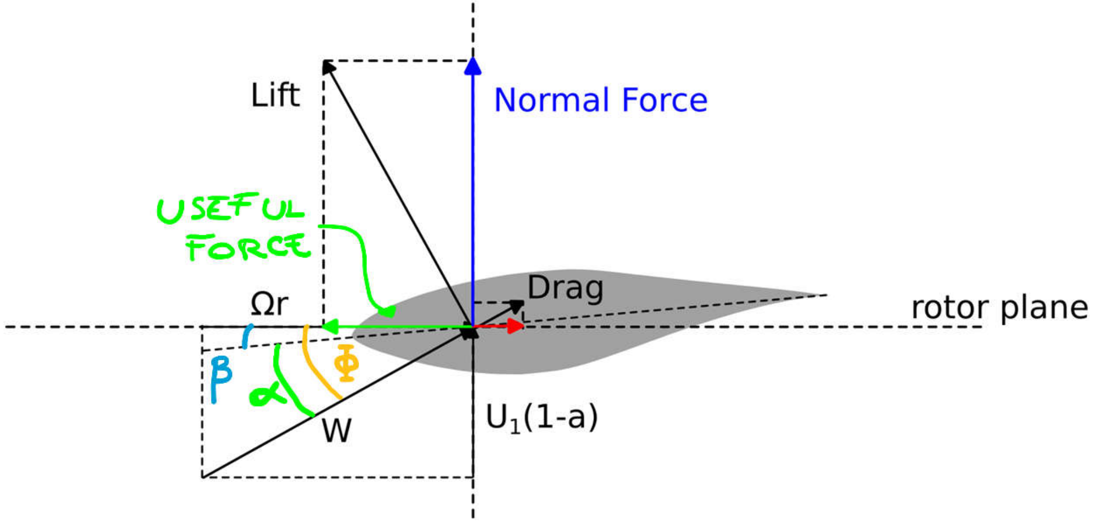
Blade design - summary

Design Objective #1: Optimal rotor force is achived for a=1/3: $F = \frac{4}{9}\rho A U_1^2$

Design Objective #2: Lift (useful force) to Drag (negative effect) ratio must be maximised

To cater to the two objectives we:

1. choose one or more airfoils for the blade - $\boldsymbol{Cl(\alpha)}, \boldsymbol{Cd(\alpha)}$
2. Choose an appropriate Tip-Speed-Ratio $\left(\mathrm{TSR} = \frac{\Omega R}{U}\right)$ as this influences the relative velocity $(\boldsymbol{W})$
3. determine chord $(\boldsymbol{c})$ and twist $(\boldsymbol{\beta})$ as a function of blade radius so that the lift-to-drag ratio of each section is maximized and the axial induction of each section is 1/3



TSR and design wind speed

TSR is the **foremost design parameter** around which all other optimum rotor dimensions are calculated

$$\lambda = \frac{\Omega r}{V_w}$$

λ = Tip speed ratio

Ω = Rotational velocity (rad/s)

r = Radius

V_w = Windspeed

Aspects such as efficiency, torque, mechanical stress, aerodynamics and noise should be considered in selecting the appropriate TSR (since it directly determines ω)

- ✓ high TSR makes centrifugal stresses increase and aerodynamics more critical
- ✓ high TSR decreases blade solidity and increase aerodynamic noise
- ✓ modern rotors generally operate with TSR between 5 and 10

Tip Speed Ratio	Low	High
Value	Tip speeds of one to two are considered low	Tip Speeds higher than 10 are considered high
Utilisation	traditional wind mills and water pumps	Mainly single or two bladed prototypes
Torque	Increases	Decreases
Efficiency	Decreases significantly below five due to rotational wake created by high torque	Insignificant increases after eight
Centrifugal Stress	Decreases	Increases as a square of rotational velocity
Aerodynamic Stress	Decreases	Increases proportionally with rotational velocity
Area of Solidity	Increases, multiple 20+ blades required	Decreases significantly
Blade Profile	Large	Significantly Narrow
Aerodynamics	Simple	Critical
Noise	Increases to the 6th power approximately	

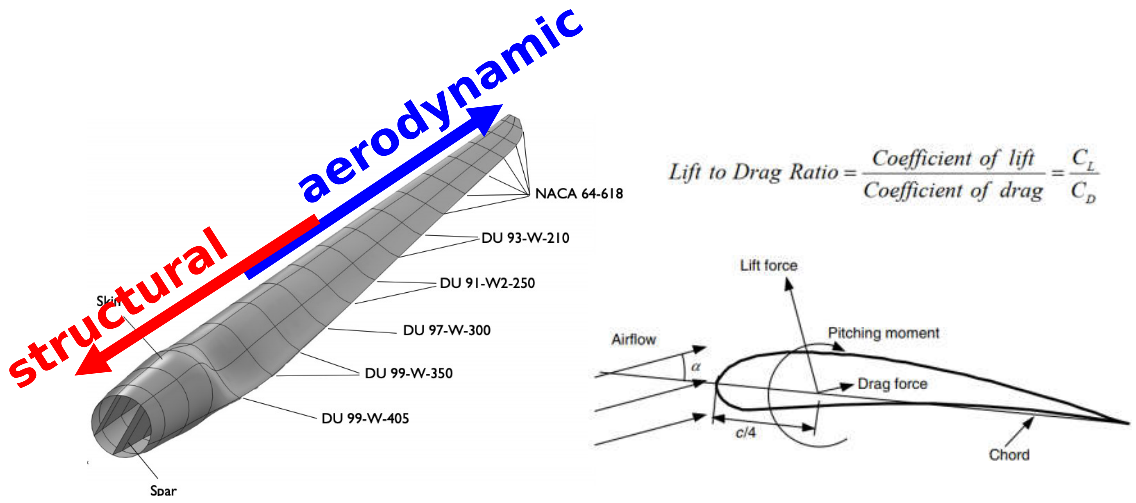
Airfoil selection

The use of a single airfoil for the entire blade length would result in inefficient design

- ✓ each section along the span has not only a different relative speed and AoA, but also **structural requirements**
- ✓ airfoil need to be tailored accordingly

At the root, the blade sections have large minimum thickness which is essential for the intensive loads to be managed resulting in thick profiles

Approaching the tip, blades blend into thinner sections with higher linear velocity and increasingly critical aerodynamic performance



The general requirement for airfoil design is a **high lift-to-drag ratio**

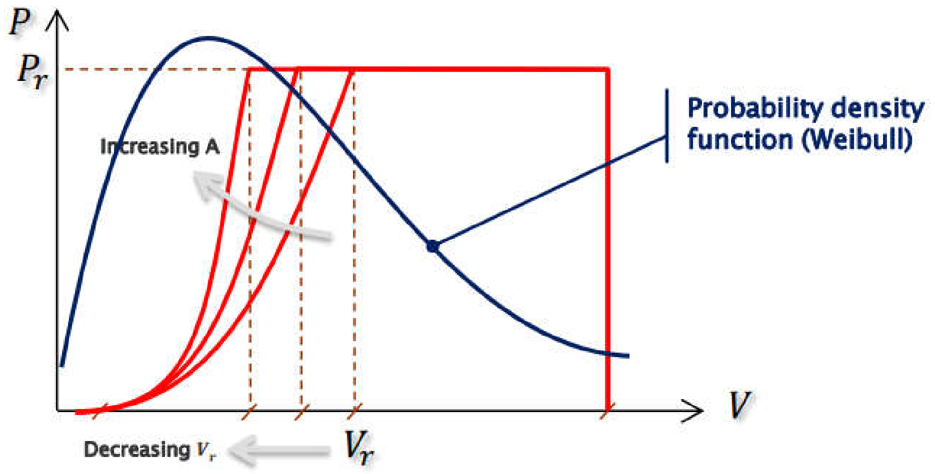
Specific power

$$P = \frac{1}{2}\rho U^3 A \overbrace{4a(1-a)}^{Cp}$$

$c_{P_{max}}$ is limited by physics -> Betz law

To increase power at a given wind speed, we can only increase rotor area

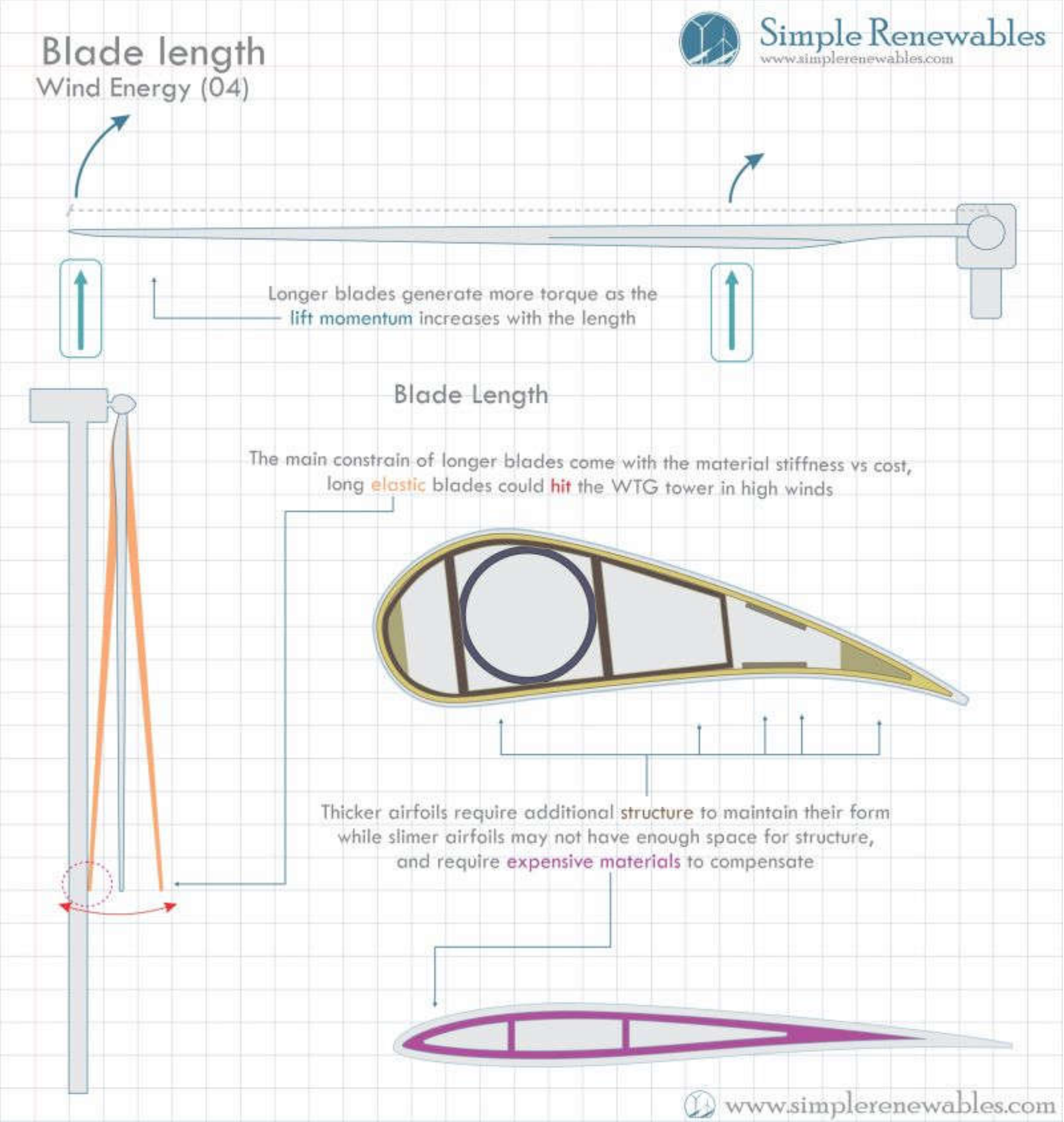
The only way is to reduce the specific loading P_{rated}/A



Credits to Prof. Carlo Bottasso, TUM

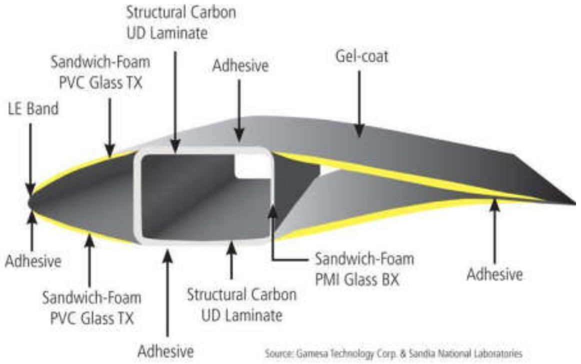
Rated wind speed → $v_{rated} = \sqrt[3]{\frac{\frac{P_{rated}}{A}}{{}^{1}/_{2}\rho c_{P_{max}}}}$

Blade structure



To reduce the weight, blades have:

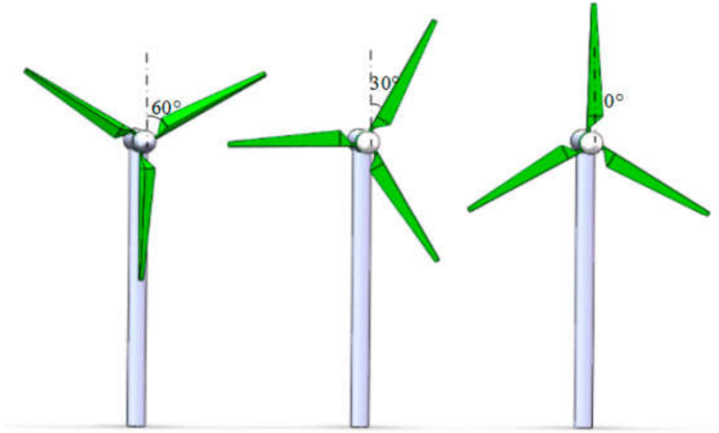
- ✓ a hollowed section, with different types of reinforcement in the section with the highest thickness
- ✓ external surface made of composite materials (plus reinforcing fibers), often molded
- ✓ multi-layer structure



Mechanical stresses

Wind turbine blades can indeed be huge

- ✓ transportation and mounting cost are often one of the main drawbacks of an installation
- ✓ their own weight can represent a serious issue
  - e.g. 5-15 ton for blade lengths from 20 to 40 m
- ✓ the structural project has to take into account a cyclic variation of the loading on the blade due to its weight:
  - Compression only ($\vartheta = 0°$)
  - Traction only ($\vartheta = 180°$)
  - Flection ($\vartheta = 90°$ and $\vartheta = 270°$)
  - Mixed loading (all other positions)
- ✓ FATIGUE PROBLEMS!



Additional “stresses” are around the corner…

from the web

Aerodynamic and centrifugal stresses

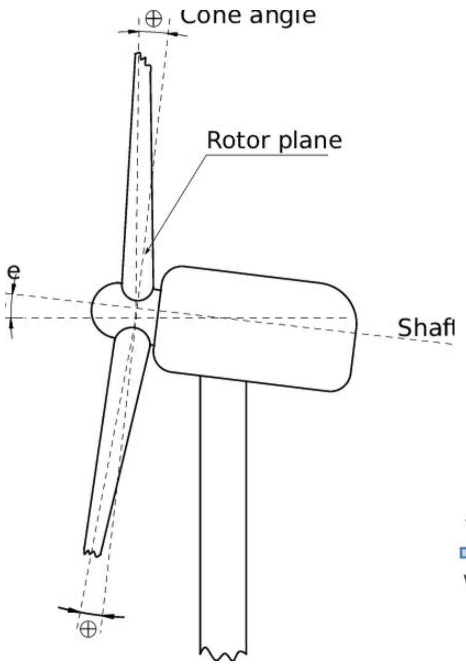
In addition to mechanical stresses, the contributions due to aerodynamic (f(V²)) and centrifugal forces must be taken into account

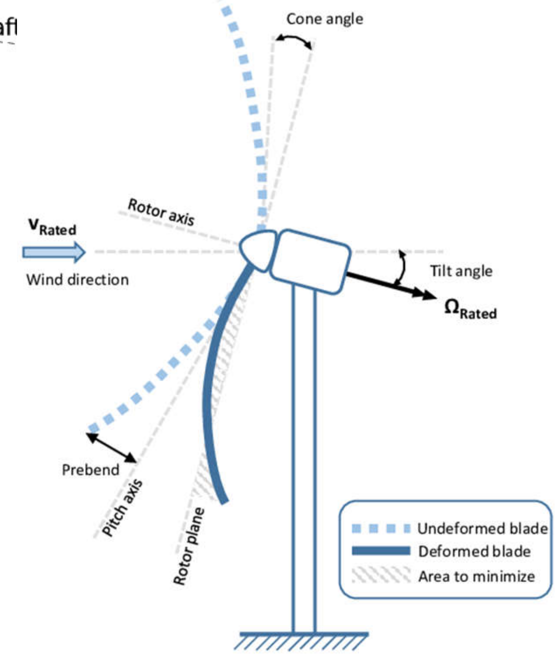
Aerodynamic forces make the blades bending in the wind direction → often built pre-bended

To balance aerodynamic and centrifugal forces, a little **cone angle** (6°-8°) is added to the blades

- ✓ the resultant force lies on the blade axis (simple traction)

A small **tilt angle** (≈ 6°) is added to the whole rotor to avoid interference between the rotor and the tower





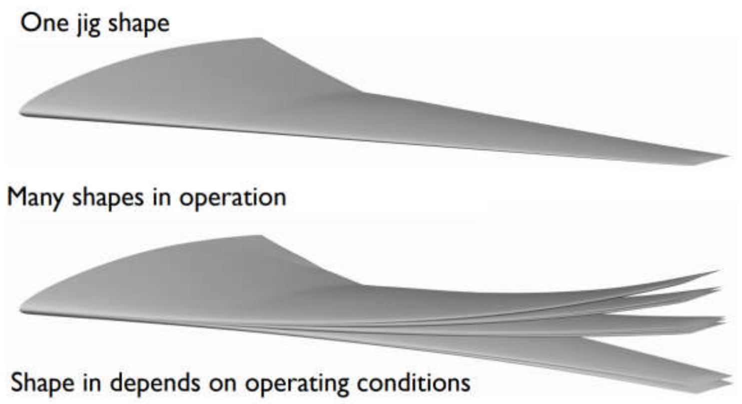
Aeroelastic tailoring

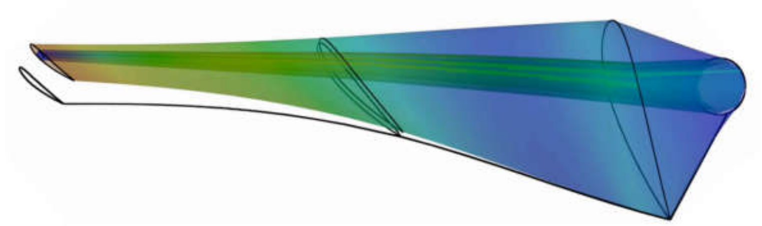
Wind turbine blades bend and twist during operation

- ✓ changes in the actual angle of attack, which in turn affects loads and energy production
- ✓ there are blades now in use that have significant aeroelastic couplings, either on purpose or because of flexible and light-weight designs

Since aeroelastic effects are almost unavoidable in flexible blade designs, it may be desirable to tailor these effects to our advantage

- ✓ efforts have been directed at adding flexible devices to a blade, or blade tip, to passively regulate power (or speed) in high winds
- ✓ it is also possible to build a small amount of desirable twisting into the load response of a blade with proper asymmetric fiber lay up in the blade skin



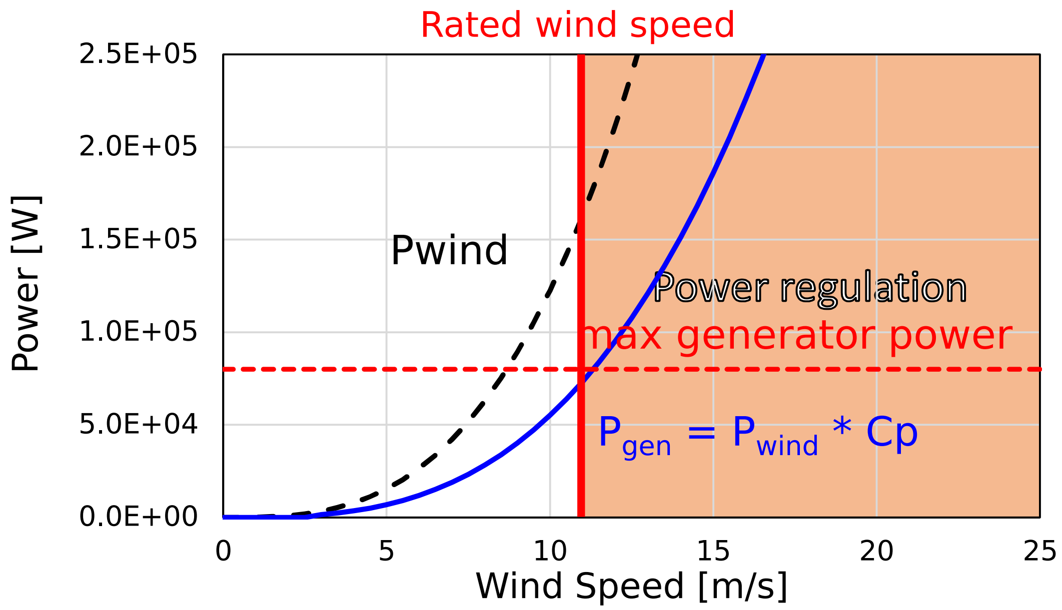


Source: J.R.R.A. Martins, Univ. of Michigan

Wind turbine operation

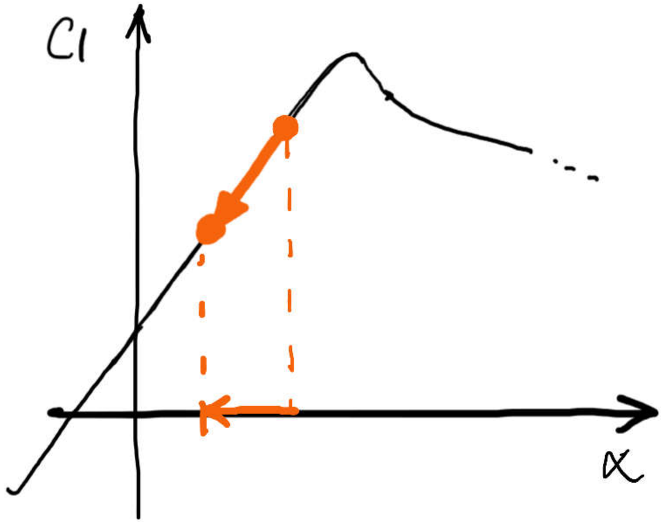
Wind turbine power curve

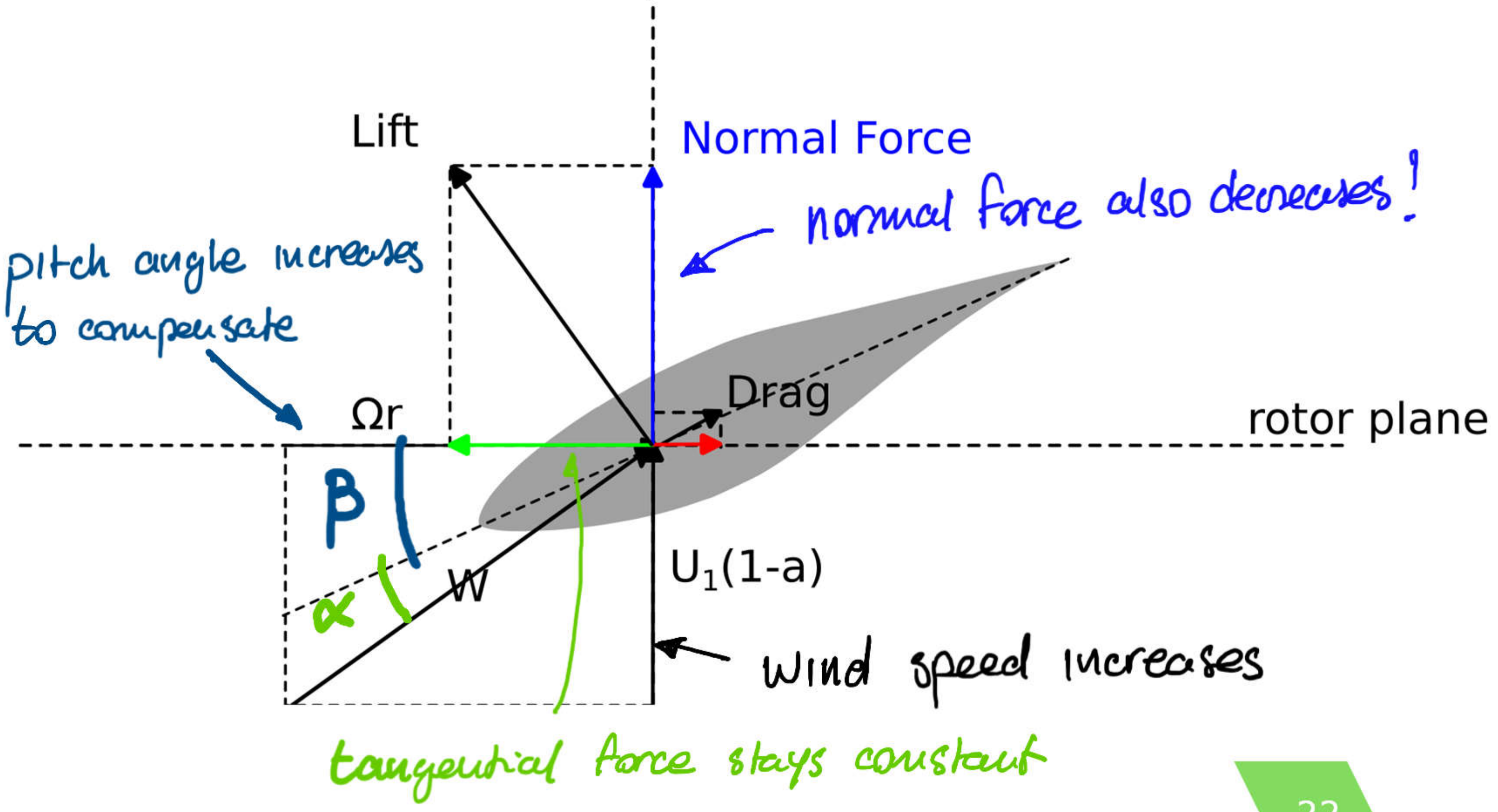
- ✓ The power a wind turbine rotor is able to produce is proportional to the cube of the wind speed
- ✓ The size of the generator imposes an upper limit on power production
- ✓ High wind speeds are unlikely, so we are not wasting that much energy by curtailing power above rated wind speed
- ✓ In order to limit power production the blades are pitched towards the wind



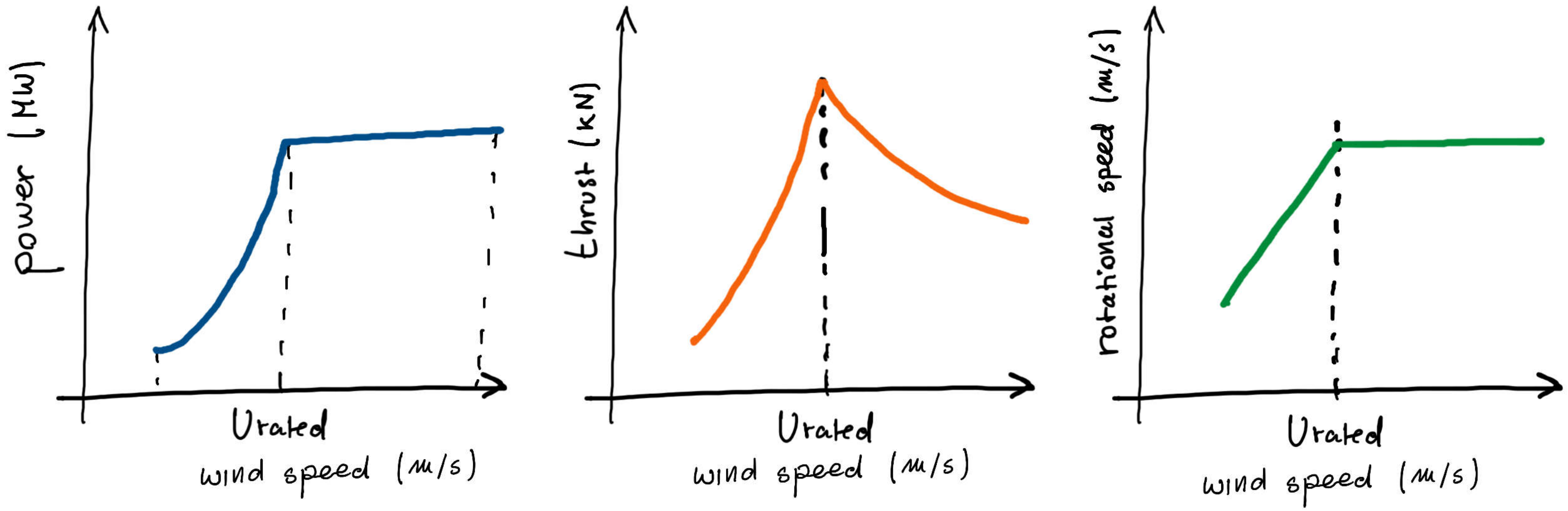
Blade pitch regulation

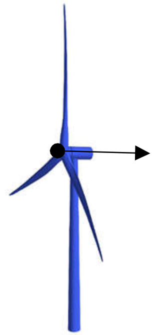
The blade is pitched to reduce the angle of attack and thus maintain constant power





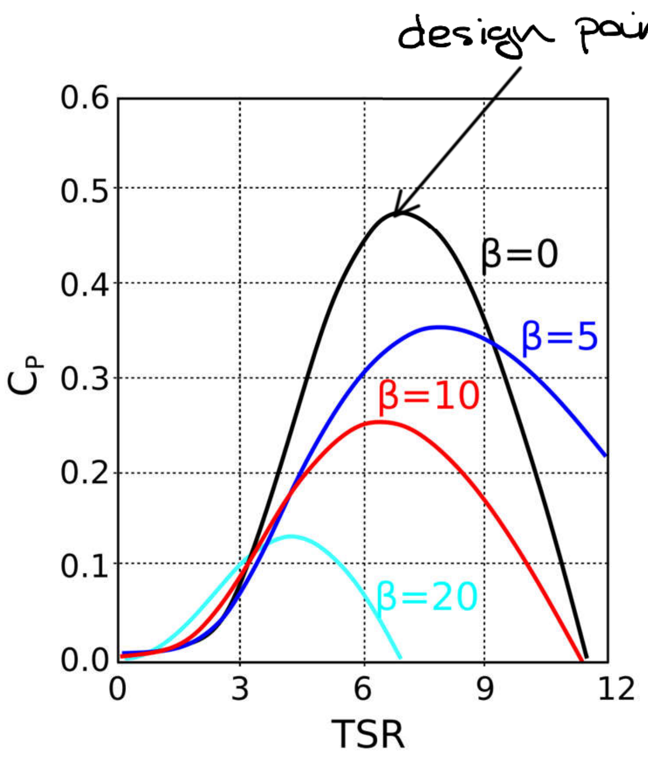
Operational curves of a wind turbine

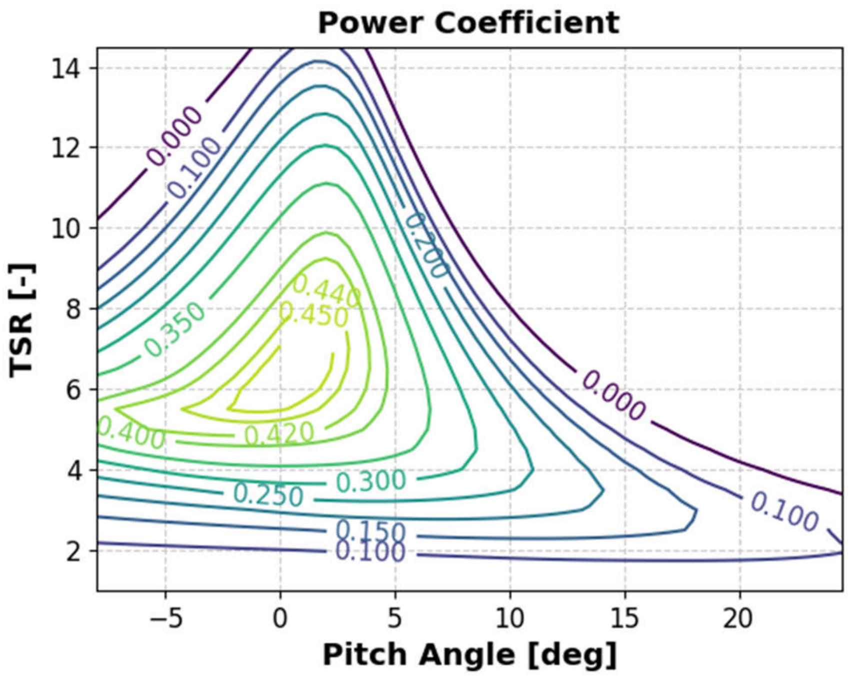




Wind turbine performance curve

Wind turbine efficiency depends on the tip speed ratio (TSR) and the blade pitch angle (β)



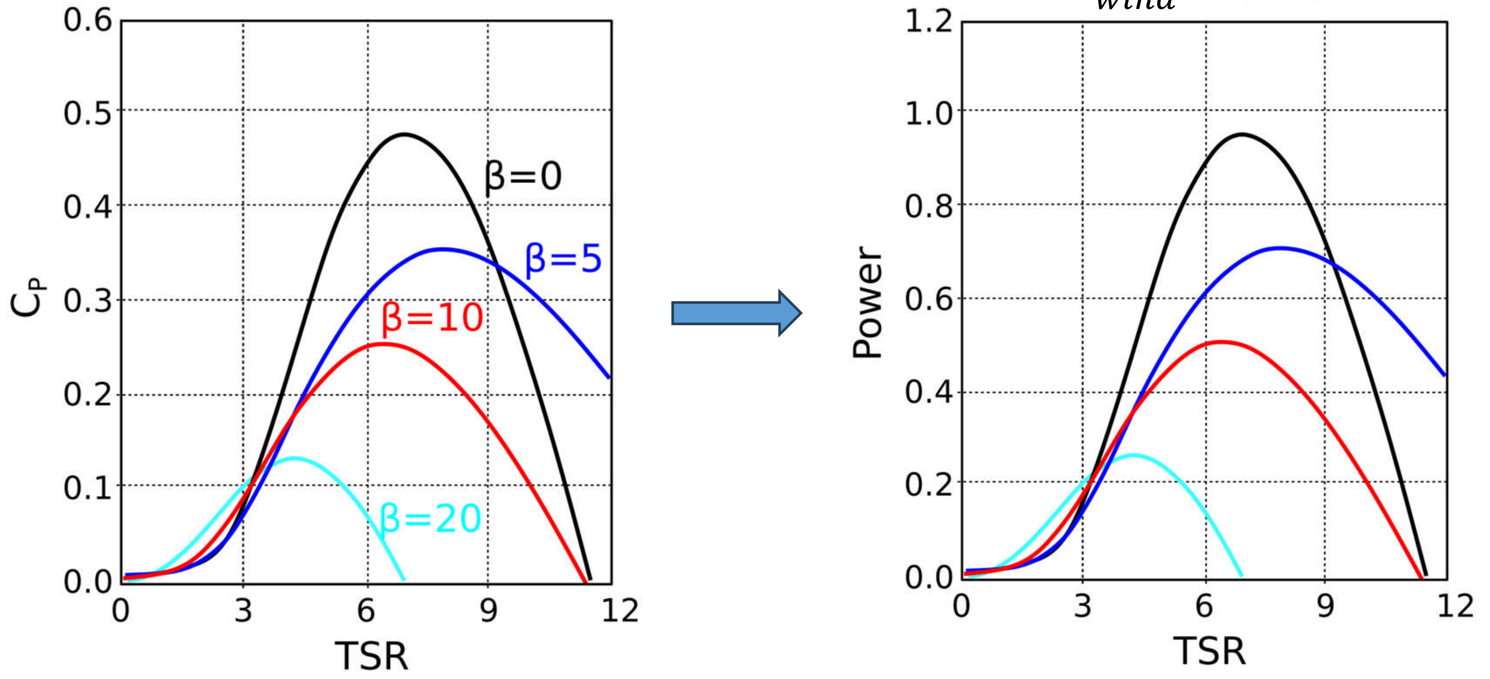


Wind turbine performance curve

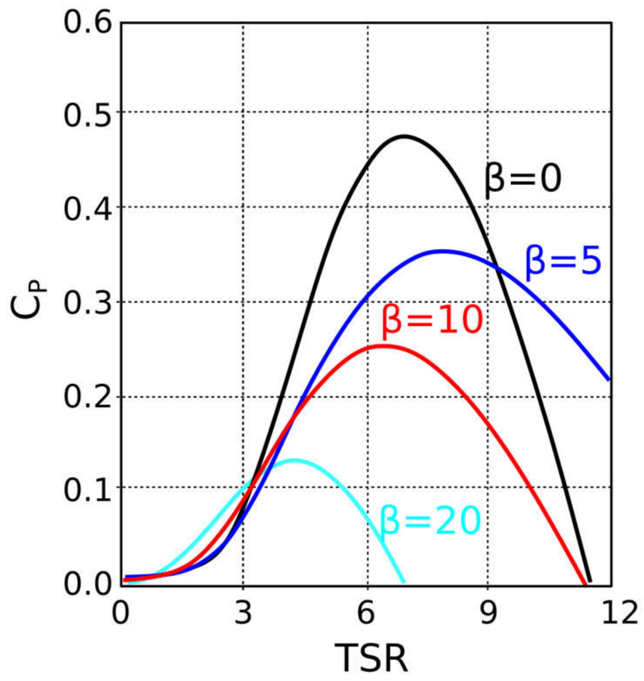
If we fix the wind speed the a-dimensional power curve (Cp-TSR) becomes dimensional

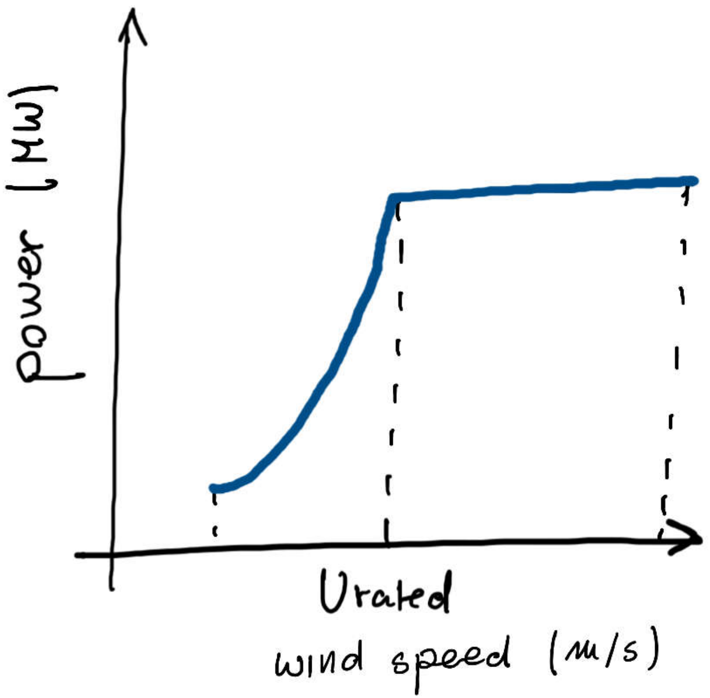
$$P = \frac{1}{2}\rho A U_{wind}^{3} Cp$$

$$U_{wind} = const$$



Performnce curves - summary





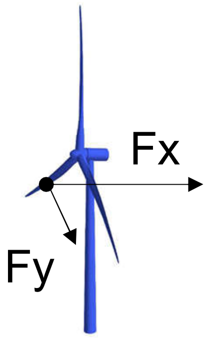
Blade force distribution – pitch control

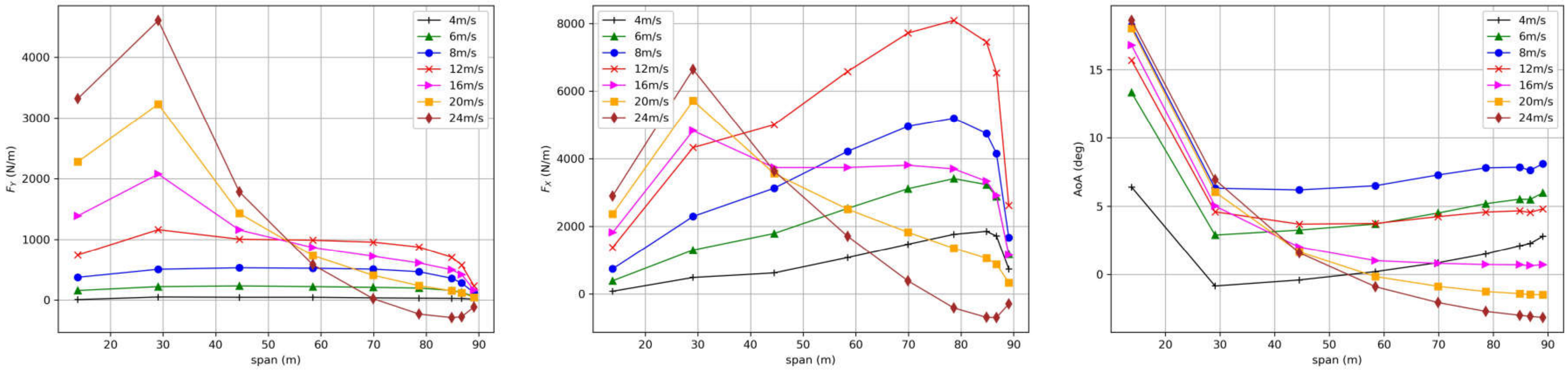
Blade forces per unit length are also mostly directed in the out-of-plane direction

Tangential forces are typically mostly “flat”, and decrease at root and tip because of tip & root losses

As wind speed increases and blades are pitched force distributions change

- ✓ Blade root produces most of the torque
- ✓ At blade tip AoA can be negative at times

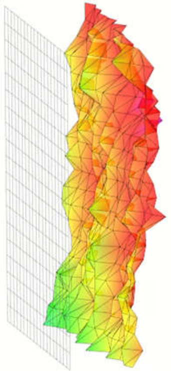


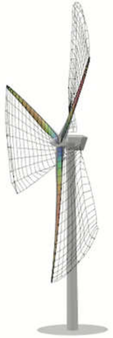


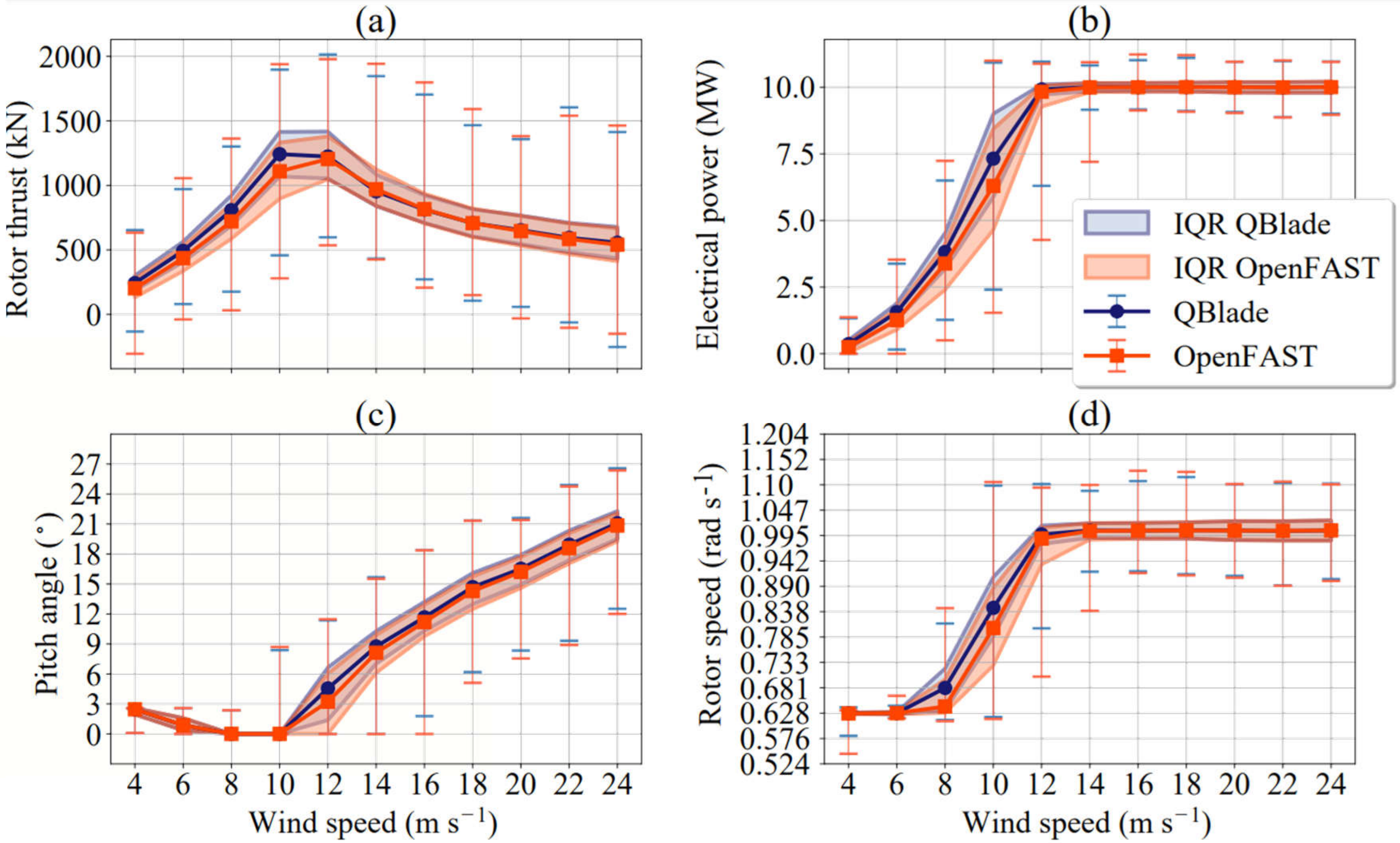
From left to right: tangential force, normal force and angle of attack along DTU 10MW RWT blade. Simulated in OpenFAST

Peak loads

Peak loads can be even two or three times the steady state loads







[7] Sebastian Perez-Becker, Francesco Papi, Joseph Saverin, David Marten, Alessandro Bianchini, and Christian Oliver Paschereit, Is the Blade Element Momentum theory overestimating wind turbine loads? – An aeroelastic comparison between OpenFAST's AeroDyn and QBlade's Lifting-Line Free Vortex Wake method, Wind Energ. Sci., 5, 721–743, 2020, https://doi.org/10.5194/wes-5-721-2020

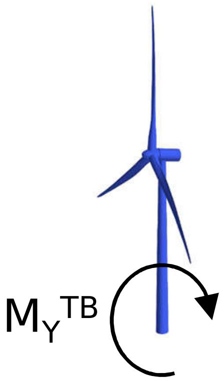
Peak loads – effect of controller

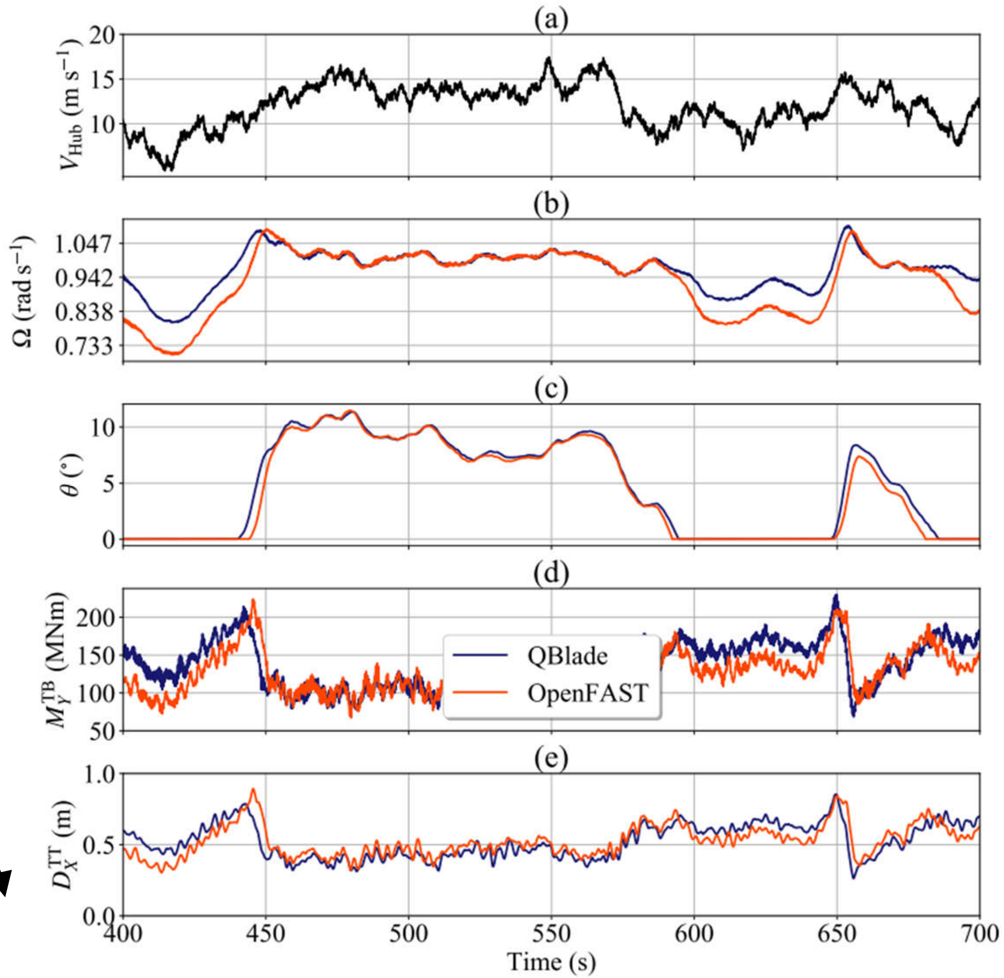
Controller can affect peak loads significantly

- ✓ tower base bending moment (M_Y^{TB}), reaches peak in correspondence of a wind gust
- ✓ Crucially, the blade pitch angle (θ) is 0° when the peak is recorded

The mechanism is as follows:

- ✓ Wind speed decreases so controller de-pitches the blades to maintain power output
- ✓ Wind rapidly increases with blades at 0° of pitch causing a high load peak in the out-of-plane direction





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