

Introduction

What are drivers for Wind Energy R&D in Europe?

CO₂ reduction through renewable energy, ~~EEG~~ EEG to it to help with investment with long-term contracts in Germany

Wind power formula ; Power coefficient formula

$$P_w = \frac{\pi}{2} \rho V^3 A ; C_p = P_T / (\frac{\pi}{2} \rho V^3 A)$$

Tip speed ratio formula ; Capacity factor formula

$$\lambda = \frac{n R}{V_{wind}} ; CF = \frac{\text{average output}}{\text{peak output}}$$

What are challenges for smaller wind turbines?

- low power production : $P \sim R^2$ $P \sim V^3$
- lower hub height means lower wind speed / higher turbulence
- harder to make accurate predictions for power generation

Airfoil aerodynamics

What is levelized cost of energy?

$$LCOE = \frac{CapEx \cdot \frac{1}{1+r} + OpEx}{AEP/1000}$$

Metric to assess the cost of electricity generation

How can aerodynamics help decrease LCOE?

- lowering CapEx → making the components cheaper / simpler / lighter
- lowering OpEx → making everything durable and easy to maintain
- boosting AEP → make the turbine generate more energy

What is the center of pressure and the aerodynamic center?

Center of pressure is the point where the resulting pressure force acts, thus, where all moments are zero (moves with α_{AoA})

Aerodynamic center is point, at which moment is (near) constant over different angles of attack ($X_N = S_{c_4}$)

What is viscous drag?

Drag created by shear stresses in the boundary layer near the airfoil wall, where due to friction, velocity is very low.

Explain trailing edge separation

- Adverse pressure gradient starts downstream of point of maximum thickness (or further up at higher α_{AoA})
- Moves forward with higher α_{AoA} until at thickest point

Explain leading edge separation

- Upstream extension of TE-separation at very high α_{AoA}
- Thin airfoils with small LE radii more prone, negative LE stall more common during storms - should be avoided because of severe load fluctuations

What are soft stall / hard stall differences?

- Soft stall: separation moves gradually towards the LE when increasing α_{AoA}
- Hard stall: turbulent separation jumps towards LE when increasing α_{AoA}
- Depends on design of main pressure recovery, strong concave pressure recovery and suction peak at LE provoke hard stall, but potentially higher lift!

Airfoil aerodynamics

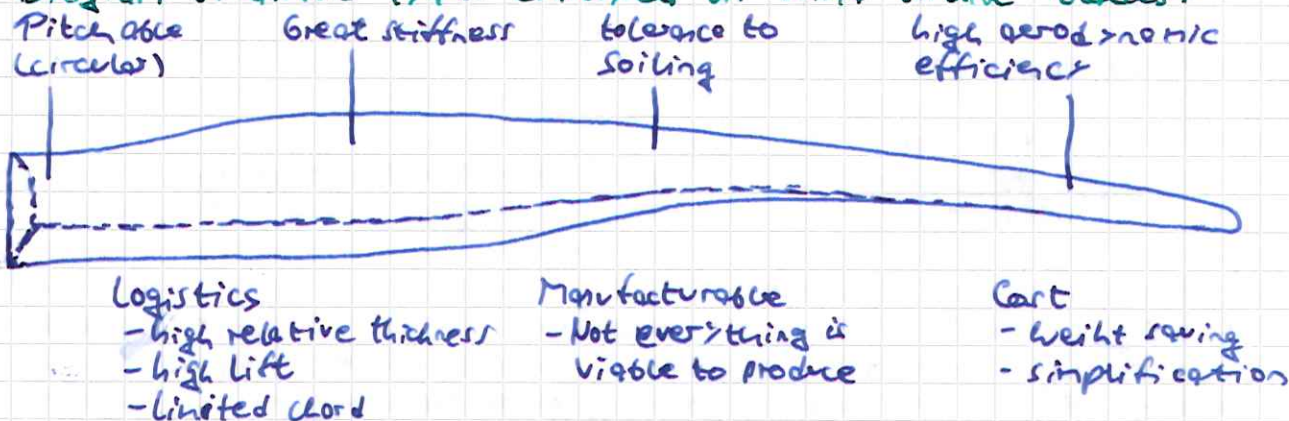
What is the effect of the Reynolds number on the airfoil?

- Boundary layer thickness decreases with rising Re
 - ↳ Viscous pressure drag decreases
- Higher $C_{l,max}$ with higher Re
 - ↳ Delay of stall, higher power output for large turbines
- Earlier laminar-turbulent transition
- Laminar drag bucket vanishes for higher Re
 - ↳ outside the bucket drag increases

Why do polars need to be manipulated to be used in blade design?

- Clean polars would be too optimistic
- Blades are often soiled by insects and dirt.
- Tripped polars too conservative → Mixed polars are used

Diagram of airfoil types employed on wind turbine blades:



What are blade design requirements in the inner, mid and outer regions?

- Blade root ~~to blade tip~~ (inner):
 - Pitchable
 - High stiffness, drag less important than lift
 - No flatback: low performance in tripped conditions, early separation, low C_l , low drag
 - Flatback: increased C_l , more drag, hard stall
- Mid blade region:
 - Higher Re -number (max is in this region)
 - The more outward, the more aerodynamic efficiency is important
 - Tolerance to soiling becomes important
 - Thin TE to reduce noise
 - Compensation of lower lift by new-loading
- Outer blade region:
 - Lower Re -number
 - Structural properties less important - Aerodyn. eff. very important
 - Wide α_{0A} range without separation due to shear
 - Minimum sensitivity against surface pollution required

List all blade add-ons and their reasons

Boundary layer fence	Inboard	Prevent non-plane separation from contaminating other blade regions
Gurney flap	Inboard	Augment sectional lift
Spoilers	Inboard	Increase lift and torque contribution
TE serrations	Mid-outboard	Attenuate trailing edge noise
Vortex generators	In-mid board	Prevent flow separation, reduce unsteady loads, increase AEP
Winglets	Outboard	Reduce tip vortices drag

Blade add-ons

Boundary layer fence

Positioned on the innermost section of the blade to prevent root-prox separation pockets from contaminating other regions of the blade

Spoilers

Inboard section of the blade at 50%-70% chord on pressure side, around 5% c high. They move the stagnation point towards the pressure side, which deflects the flow downward (towards the pressure side) creating lift.

Vortex generators

Inboard section of the blade ^{near} leading edge on suction side. They are small fins inclined to the flow inside the boundary layer. ~~They~~ They create a ~~primary vortex~~ primary vortex which pulls down fluid with larger momentum towards the rear wall region ~~where separation~~

- later separation in root region
- higher stall angle
- higher lift

Gurney flaps

Root region of the blade as extension of trailing edge towards pressure side. Flow is deflected towards pressure side, higher stream line curvature, more lift!
 - But: higher suction peak in the front region
 - Rear loading in the pressure side increases

Serrations

Between 70%-100% of the blade radius at trailing edge to reduce noise, but has further aerodynamic effects:

- Flap angle / aerodynamic loading creates trailing vortices around sides
- With increasing flap: more lift, more induced drag
- with increasing length: viscous drag increases,

Winglets

Reduces size of tip vortex and thus induced drag of the blade, increases power by 1%-2%. Must be bent towards pressure side for lower clearance

What is dynamic stall?

Massively separated flow which includes all complex characteristics, unsteady excitation from angle of attack variation. Rapid α change can induce LE vortex, which induces stall on the wing.

How is the unsteadiness of an aerodynamic problem described?

$$k = (\pi f c) / (U_\infty)$$

$\swarrow$ Lchord
 $\swarrow$ Pitching frequency
 $\swarrow$ P_i (ups:iii)

Steady-state aerodynamics at $k \approx 0$

What is the tip loss effect?

Momentum theory assumes constant loading across rotor plane - not accurate. Loading is highest in blade locations and variation becomes greater near the tips, where 3D effects become more prominent. Actual lift is smaller because of this blade tip loss factor.

What is the Himmelskamp-Effect?

Coriolis towards TE

Stall delay due to Coriolis force - centrifugal force - interactions on the blade (more prone in outer regions) Also better lift

Airfoil aerodynamics

What are examples of dynamic stall models?

Indicial formulation / state space representation

- Oye model (1 state)
- Beddoes model (5 states)
- IAG model (5 states)
 - 2 attached flow states
 - Pressure lag state
 - Separated flow state
 - Vortex lift state

What is a wake?

Less energetic, turbulent and rotating flow behind the turbine

What are characteristics of the near wake?

Rotates in opposite direction to rotor (conservation of momentum)

Strength of rotation decreases with distance

Strong tip vortices, break down at end of near wake (vortex pairing)

What are characteristics of the far wake?

3D - 70D behind turbine, grows in lateral and vertical size, streamwise velocity gradient recovers with distance

Described with Jeter model / Frandsen model / Bortnikhah, Porté-Agel model

How could we quantify wind turbine loads?

Combination of Momentum theory with blade element theory gives BEM

BEM procedure builds up loads element by element, then integrates along the blade to get dimensionless coefficients C_{ax} , C_p and C_t, q'

How to do that in reasonably accuracy?

Result breaks down under real conditions, so corrections are applied:

- Tip-loss correction: F_{tip}
- Turbulent wake state correction: empirical relations for C_t and q are needed once q exceeds 0.5
- 3D rotational augmentation (Hinnelkamp effect)

BEM low-cost alternative to CFD but needs corrections.

Under which conditions is the steady-momentum model no longer valid?

When core momentum theory assumptions no longer apply:

- 7-Dimensional
- steady, uniform inflow across the rotor disk

This happens during turbulence, control actions, wind shear, tower shadow, dynamic stall, ...

How can these unsteady phenomenon be modeled?

BEM is steady, but unsteadiness can be added. Unsteady BEM:

- Turbulence: local wind sampled directly
- Dynamic wake: Oye model
- Dynamic stall: Leishman-Beddoes-model
- Wind shear: Power law / log law next to wind profiles
- Yaw misalignment:
- Tower shadow:

For VAWTs, plain BEM does not apply, instead, use Double Multiple Stream tube model (DMS) or (IDMS)

Fundamentals of acoustics

Why is wind turbine noise important?

Turbines are built in areas with lower wind speed (less speed) - so larger rotors needed
 Max. rpm and TSR are capped - turbines get larger but not louder
 New turbines are closer to urban areas, new regulations need to be met.

What's the speed in solid materials / general fluids / air?

$$C_0 = \sqrt{G/\rho} \quad / \quad C_0 = \sqrt{\kappa/\rho} \quad / \quad C_0 = \sqrt{\gamma RT}$$

↳ shear modulus ↳ bulk modulus of elasticity

What are the main parameters describing sound?

Tone color / height is described by frequency of pressure wave
 Volume is described by average amplitude of the pressure wave

What are basic aeroacoustic sources?

Moving volume: blades passing through air (monopole)
 Turbulence, pressure fluctuations close to a wall: interaction of blades with incoming turbulence, Directivity and M -scaling depends on compactness
 Free turbulence: Only relevant for very high M -numbers (Quadrupole)

How is human hearing characterized and how are we affected by noise exposure?

Human hearing ranges over several orders of magnitude

0 dB hearing threshold, 120 dB pain threshold, 140 dB irreversible damage

- Sound pressure level: $L_p = 20 \log \left(\frac{P_{rms}}{P_0} \right)$
 property given at an observer location
- Sound intensity: $I = P_{rms}^2 / \rho_0 C_0$
 power transmitted per unit area
- Sound power level: $L_w = 10 \log \left(\frac{P}{P_{ref}} \right)$
 property of the sound source
- Acoustic impedance: $Z = \rho_0 C_0$
 resistance against sound propagation

Noise disturbs concentration, sleep, ... High levels can cause fatigue, headaches, ...
 No effects below the perception threshold

A-weighting to take into account that humans are most sensitive to 1 kHz - 4 kHz

Noise emission

How can the sound sources at a WT be characterized?

By the location of the source:

- Blades: interaction with flow, turbulence, scales with rpm
- Generator / gearbox in hub: low frequency tones
- Further sources in hub and tower base: higher frequency tonalities

Which aerodynamic / secondary noise sources do exist?

Aerodynamic

TE noise

Stall noise

Blunt TE noise

Inflow turbulence noise

Tip noise (tip vortex)

Tower-blade interaction

Surface imperfections

Secondary

Gearbox

Generator

Cooling fans

Current transformation

Yaw / Pitch drives

Turbulent pressure fluctuations that create interaction with the airfoil / tower

Vibrations travelling through the metal and propagating through other components to produce sound

Noise emission

~~What are the noise sources behind different noise sources?~~ What are the noise sources present at modern wind turbines?

All of those mentioned before are present in modern wind turbines, with TE noise being the most dominant in the audible range and turbulent inflow the second most dominant one.

Which are the most annoying sources and how can they be reduced?

Tonal noise is penalized separately in regulations because it is perceived more annoying than broadband noise of the same level (whistling, generator low freq.) This can be reduced with:

- generator: isolation of emitting surface / exciting part, use polished gear
- cooling fans: design to need less, reduce inflow velocity
- TE noise: avoid stall, minimize boundary layer thickness, avoid over-induction, use rotated TE, boundary layer suction
- Blunt TE noise: use wedge angles smaller 45° to reduce amplitude

Noise prediction

Which approaches exist for noise prediction?

Empirical models (cheapest, least detail)

Simplified analytical or semi-empirical models (intermediate)

Computational aerodynamics (most detail, most expensive)

Which methods are the current state of the art for each mechanism?

TE-noise: empirical BPM-model and the semi-empirical / physics based TNO-type-model

Inflow-noise: Amiet-model (with Lawson extension for low frequencies and Moriarty correction for finite airfoil thickness)

How do these models work / what are drawbacks and advantages / what are limitations?

BPM: derived from specific profile at specific Re-number at a range of α and δ^* . Purely empirical scaling law, only requires local Re-number, boundary layer displacement thickness δ^* , angle of attack, observer distance and blade span.

Very simple, only requires few inputs, very fast and has reasonably good prediction accuracy. Doesn't account for airfoil shape, typically overpredicts high frequencies.

Fixed airfoil derived, empirical Re, α ranges from original wind tunnel data

TNO: Starts from RANS CFD to get boundary layer statistics (turbulence length scale, Reynolds stresses, mean shear), plugs these into wall-pressure-fluct-equation.

Physics derived, depends on real turbulence statistics, works for any airfoil shape, relatively cheap, but: needs CFD and cannot capture trailing-edge serrations

Assumes locally 2D, well bounded turbulence with modeled anisotropy. For fixed propagation assumes straight edge - no serrations

Amiet: Derived analytically for a flat plate in turbulent stream. Lawson-low-frequency model adds low-frequency-correction, Moriarty correction to account for finite leading-edge-thickness (not flat plate). Doppler effect included.

Needs turbulence spectrum inputs and corrections to be usable, relatively expensive

Source superposition assumption (each blade section treated separately)

Noise immission

Which factors influence the physics of propagation?

- Geometrical spreading (6dB per distance doubling)
- Atmospheric attenuation (viscous absorption of high frequencies)
- Refraction (bending of sound waves due to temp, wind speed gradients)
- Ground reflection (interference between rays)
- Shielding / diffraction (obstacles)

44

Which regulations exist for the noise from wind turbines or farms?

Bundes-Immissionschutzgesetz is the federal law, its administrative instruction TA Lärm sets the allowed reference immission values. Propagation is handled by the Interimverfahren

What is the main content of the regulations?

TA Lärm defines immission reference values outside buildings by area type and day / night. Also defines 'impaired area' (a turbine is only relevant if receiver is within certain dBS limit. Uncertainty budget is added. Interim procedure mandates treating every turbine as single omnidirectional sound source at hub height and drops reflection off of ground

How are propagation calculations usually performed?

General computational methods available (linearized euler equations, ...) ^{ray methods} but too expensive for whole wind farm.

Three steps in practice:

- 1 - compute equivalent continuous sound pressure per octave band
- 2 - sum the octave bands
- 3 - apply meteorological correction to represent long term conditions

How can the yield of a wind farm be optimized under the boundary conditions imposed by sound?

Gather turbine coordinates, relevant immission points, other sound sources and sound power level data from range of operating modes.

Run this through commercial software against TA Lärm reference values to get a map of predicted sound levels

Optimization step then adjusts layout and per-turbine operating modes to satisfy the limits everywhere while minimizing energy loss.

