Wind Field Generation

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06.09.2024

Lecture #7
Controller Design for Wind Turbines and Wind Farms

Hochschule Flensburg
University of Applied Sciences

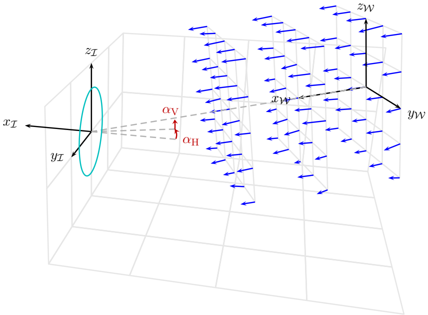
SWE Stuttgart Wind Energy
@ Institute of Aircraft Design

Wind Energy Technology Institute

Schedule

02.09.	1	Controller Design Objectives and Modeling
03.09.	2	Baseline Generator Torque Controller
04.09.	3	Collective Pitch Controller
05.09.	4	Filter Design
06.09.	7	Wind Field Generation
09.09.	10	Lidar-Assisted Control I
10.09.	11	Lidar-Assisted Control II
11.09.	5	Tower Damper
12.09.	6	Advanced Torque Controller
12.09.	8	Steady State Calculations
16.09.	9	Individual Pitch Control
17.09.	12	Wind Farm Effects
18.09.	13	Wind Farm Control
19.09.	14	Floating Wind Control I
20.09.	15	Floating Wind Control II

Wind Field Generation



Motivation

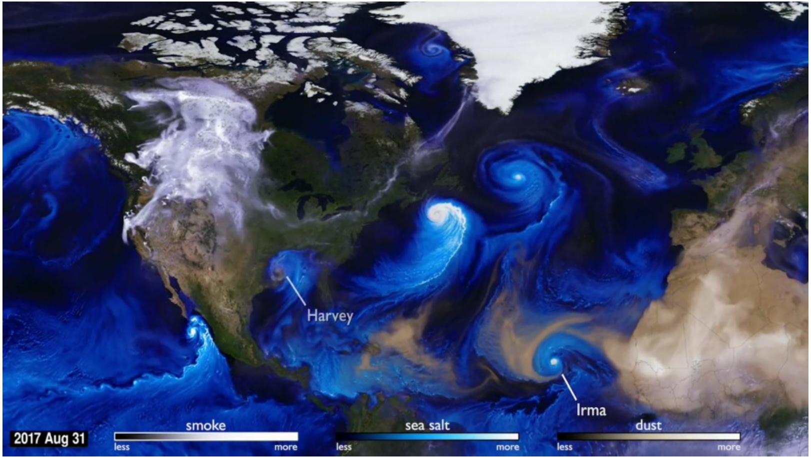
- Wind is not totally random.
- Understanding of wind is crucial in wind energy!

Main questions

- How is a turbulent wind field generated?
- How can we generate rotor-effective wind speed?

Content

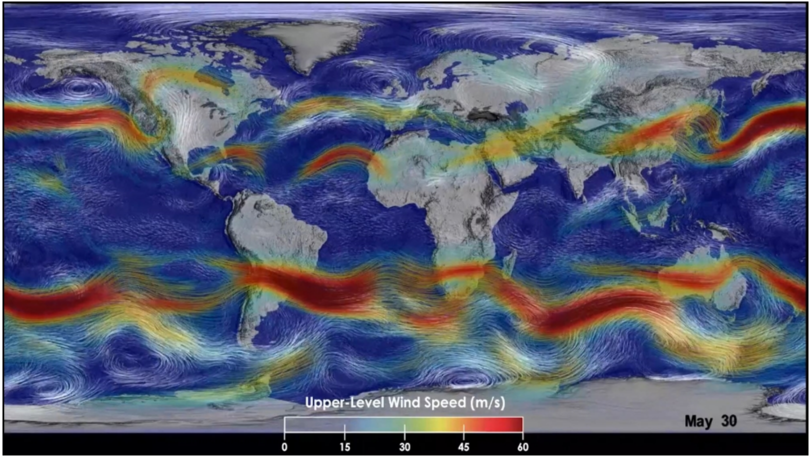
Dust in the Wind



[NASA Visualization Explorer]

- Saharan dust is swept into the outer cyclonic winds of tropical storm Irma.
- Rain at the center of the storm washes it out of the air.

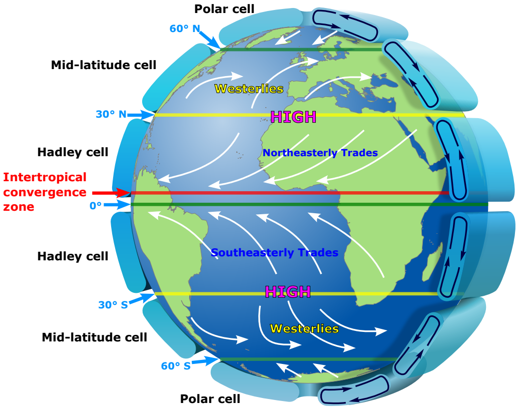
Global Wind



[Surface and Upper-Level Winds]

- High altitude winds circumnavigate the earth in wave-like paths from west to east
- Winds closer to the ground are trade winds, west winds and polar east winds

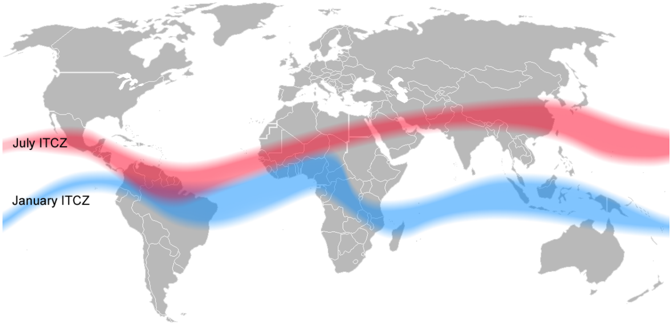
Atmospheric Circulation



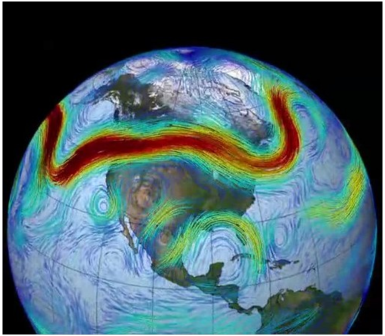
based on [wikipedia]

- As a result of different levels of solar heating, warm air rises at the equator and falls at the poles
- Wind as a compensatory movement
- Because of the rotation of the earth (Coriolis force), movements are deflected to the right in the northern hemisphere and to the left in the southern hemisphere
- Three wind systems through surface convergence

Inter-tropical Convergence Zone



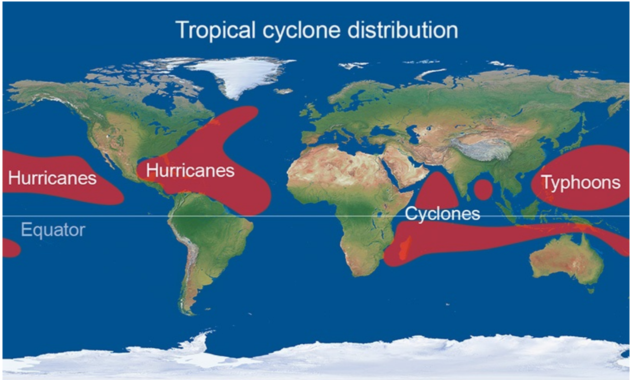
[wikipedia]



[NASA/Goddard Space Flight Center]

- Also equatorial low pressure belt or ITCZ (Inter-tropical Convergence Zone)
- Due to different land mass distribution and solar warming it is not constantly 0°
- Trade winds on both sides of the ITCZ for rapid ocean crossing
- A hurricane, cyclone or typhoon often occurs here
- Westerly winds to compensate: polar front jet stream (60°), subtropical jet stream (30°)

Location and naming of tropical cyclones

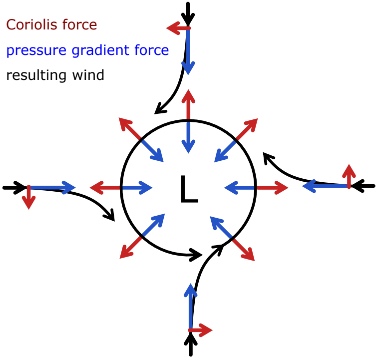


[www.metoffice.gov.uk]

- Hurricanes - Atlantic and North-East Pacific Oceans
- Typhoons - North-West Pacific Ocean
- Cyclones - South-West Pacific and Indian Ocean

Geostrophic wind

[NASA visible earth]

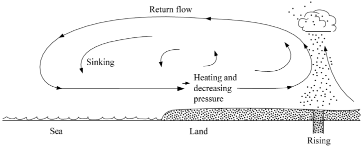


based on [wikipedia]

- Air flow at high altitudes unaffected by ground friction
- Balance between gradient force and Coriolis force
- Currents around low pressure areas in the northern hemisphere counterclockwise

Video: Coriolis force

Local winds



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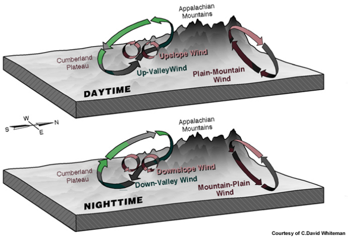


[wikipedia]

Sea-Land-circulation

- Daily cycle due to different heat capacity
- Sea wind during the day: land warms up faster
- Land wind at night: land cools down faster

Mountain-valley-circulation

- Daily cycle due to different proximity to the ground
- Valley wind during the day: the air on the mountain slope warms up
- Mountain wind at night: air on the mountain slope cools down

Formation of the Atmospheric Boundary Layer

Atmospheric Boundary Layer

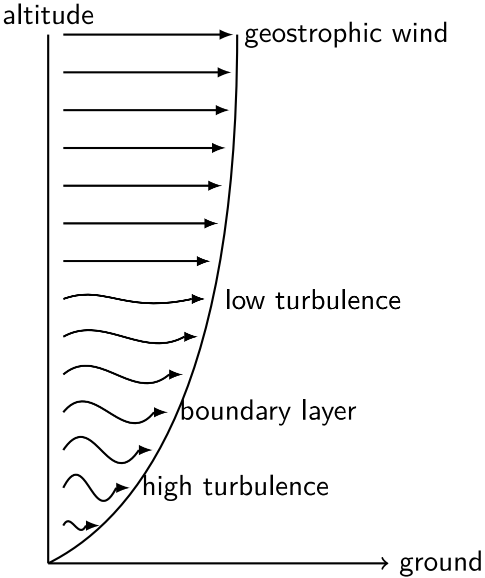
- High altitude → geostrophic wind
- Ground → no wind speed

Energy extraction by ground roughness

- Vertical wind speed gradient
- Turbulent momentum and mass exchange with higher air layers

Boundary layer thickness

- From $100\,\mathrm{m}$ on cold nights.
- Up to $2000\,\mathrm{m}$ on warm summer days with low wind speed
- On average approx. $1000\,\mathrm{m}$



Vertical Temperature Profiles

Unstable

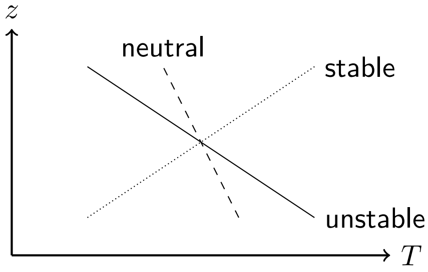
- Air near the ground is warmer than the air above.

→ There is more vertical mass transfer and thus increased turbulence

Stable

- Air near the ground is colder than the air above.

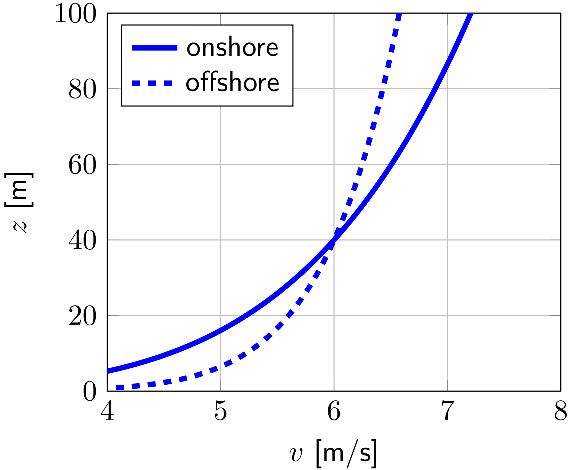
→ There is less vertical mass transfer and turbulence is suppressed



Neutral

- adiabatic temperature profile (no heat interaction, only caused by pressure)
- Air temperature decreases by about 1°C per 100 m increase in altitude.
- Often occurs at high wind speeds

Exponential Wind Profile



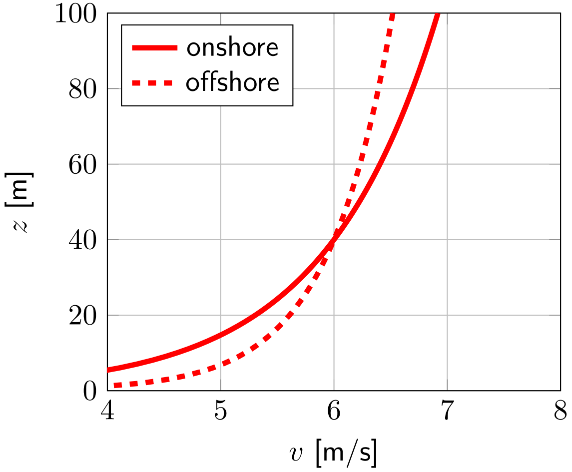
$$v_2 = v_1 \left(\frac{z_2}{z_1}\right)^{\alpha}$$

v_1 wind speed at height z_1
v_2 wind speed at height z_2
α roughness exponent

Roughness exponent α:

0.1	desert, open sea
0.15	meadows, pastures
0.2	little vegetation
0.37	cities, forest

Logarithmic Wind Profile



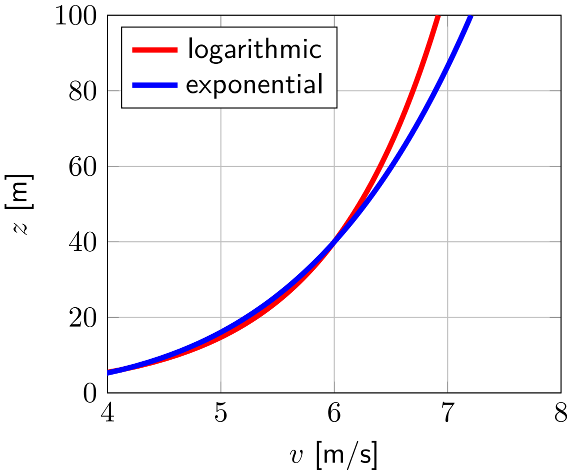
$$v_2 = v_1 \frac{\ln(z_2/z_0)}{\ln(z_1/z_0)}$$

v_1 wind speed at height z_1
v_2 wind speed at height z_2
z_0 roughness length

Roughness length z_0

0.001 m	desert, open sea
0.01 m	meadows, pasture
0.1 m	little vegetation
1 m	cities, forest

Logarithmic and Exponential Wind Profile



$z = 40\,\mathrm{m}$ and $v = 6\,\mathrm{m/s}$

$z_0 = 0.1\,\mathrm{m}$
$\alpha = 0.2$

Influence of Stability on Wind Profile

Unstable thermal stratification

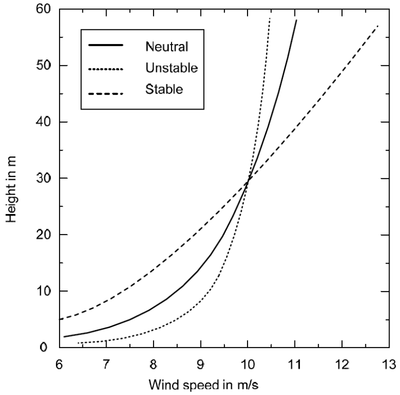
Rising air leads to strong vertical mass transfer and turbulence.
$\rightarrow$ Slope of wind velocity with increasing altitude becomes smaller.

Stable thermal stratification

No vertical mass transfer and thus no turbulence.
$\rightarrow$ Strong gradient of the wind profile.

Neutral thermal stratification

An adiabatic temperature profile is present.
$\rightarrow$ Gradient of the wind profile decreases with the altitude.

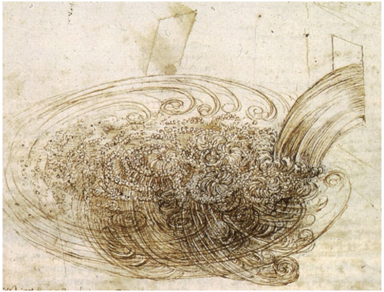


[1]

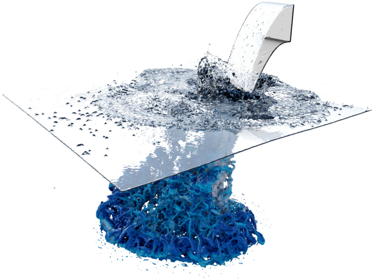
Turbulence (Intensity)

Terminology:

- Turbulence describes a flow condition of the air that is characterized by disorder
- Turbulence intensity describes the ratio of the standard deviation of the wind speed to the mean value of the wind speed related to a time interval of 10 minutes



[Leonardo da Vinci], ca. 1510-12

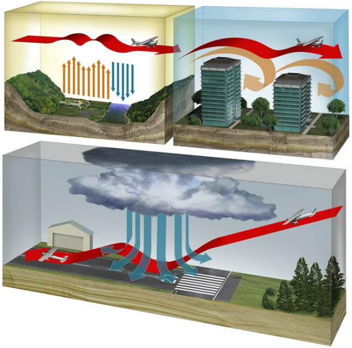


3D-Illustration von [Paolo Colagrossi]

Atmospheric Turbulence

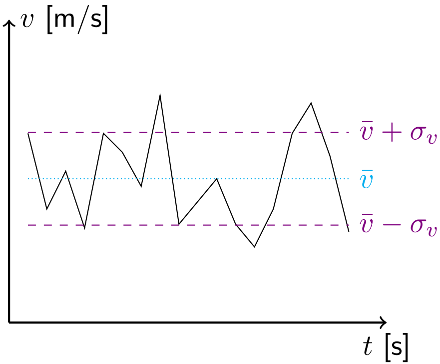
Causes

- Mechanical: caused by vertical shear and viscosity of the air, depends on local winds and roughness
- Thermal: caused by heat convection due to temperature differences



[Kevin Hand]

Turbulence Intensity



Mean wind speed $\bar{v}$

$$\bar{v} = \frac{1}{T}\int_0^T v(t)\mathrm{d}t \qquad \text{continuous}$$

$$= \frac{1}{n}\sum_{i=1}^{n} v_i \qquad \text{discrete}$$

Variance σ_v^2 and standard deviation σ_v

$$\sigma_v^2 = \frac{1}{T}\int_0^T (v(t)-\bar{v})^2\mathrm{d}t \qquad \text{continuous}$$

$$\sigma_v^2 = \frac{1}{n-1}\sum_{i=1}^{n}(v_i-\bar{v})^2 \qquad \text{discrete, Bessel's corr.}$$

$$\sigma_v = \sqrt{\sigma_v^2}$$

Turbulence intensity I_V

$$I_V = \frac{\sigma_v}{\bar{v}}$$

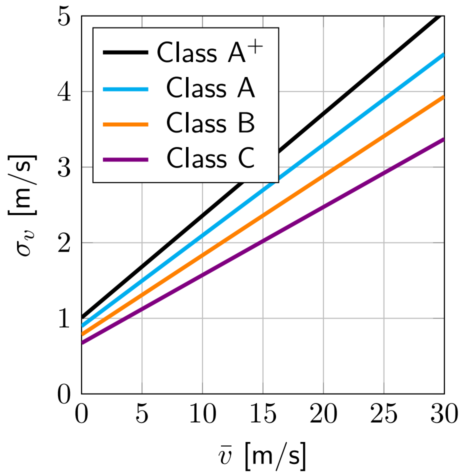
WTG Classes acc. to IEC 61400-1 with Turbulence Classes

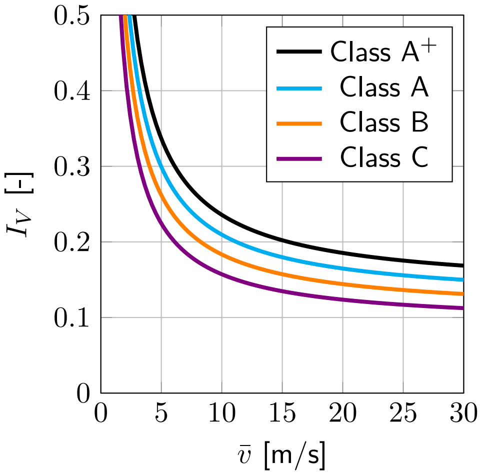
Wind Turbine Class		I	II	III	S
V_{ave}	(m/s)	10	8.5	7.5	Values specified by the designer
V_{ref}	(m/s)	50	42.5	37.5	
	Tropical (m/s)	57	57	57	
$V_{ref,T}$	(m/s)	57			
A+		0.18			
A		0.16			
B		0.14			
C		0.12			

Extract from [IEC 61400-1]

V_{ref}	reference wind speed
$V_{\text{ave}} = 0.2V_{\text{ref}}$	annual mean wind speed at hub height
I_{ref}	expected value of the turbulence intensity at $15\,\text{m/s}$
A^{+}, A, B, C	turbulence class
σ_v	standard deviation of longitudinal wind component at hub height
v_{hub}	wind speed at hub height

Normal Turbulence Model (NTM) acc. to IEC 61400-1

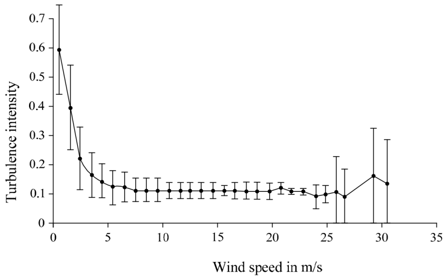




$\sigma_v = I_{\text{ref}}(0.75\bar{v} + b)$ with $b = 5.6\,\text{m/s}$

$I_V = \frac{\sigma_v}{\bar{v}}$

Turbulence intensity from measurements



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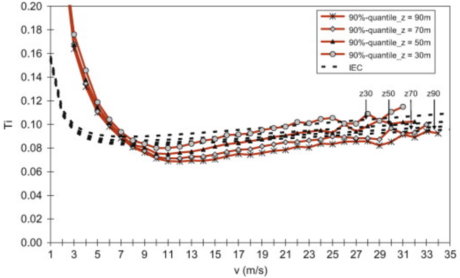


[Matthias Türk, Stefan Emeis]

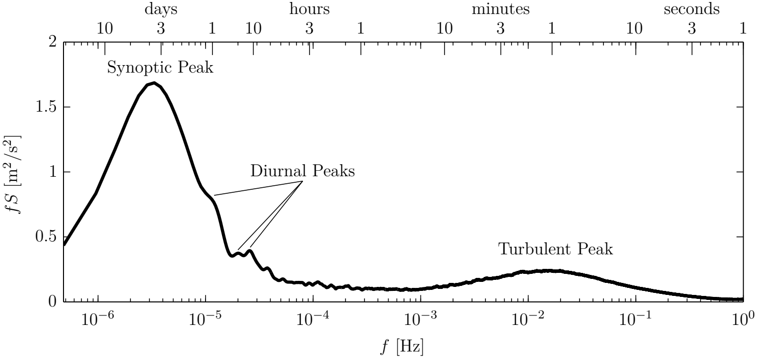
Onshore

- I_V is reduced with increasing wind speed
- at low wind speeds I_V is strongly depending on the atmospheric stability

Offshore

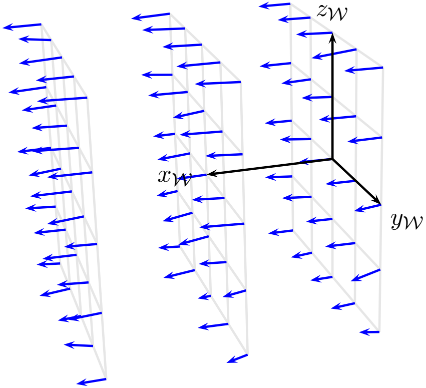
- Wind speed is influencing wave formation and by that the roughness
- Roughness and wave height are usually increasing with the wind speed $\rightarrow I_V$ is increasing

Spectral Gap



- Wind spectrum from Bremerhaven measured at $44\,\text{m}$, averaged over 4 months [2].
- The peaks at around 10 and 14 hours are caused by land and sea breezes.
- The wind speed variations with a timescale of minutes or less are known as turbulence.
- The spectrum drops before the turbulence region as in [3].

Introduction to Turbulence Models



"When I meet God, I am going to ask him two questions: Why relativity? And why turbulence? I really believe he will have an answer for the first."
- Werner Heisenberg -

IEC Kaimal Spectral Model [4]

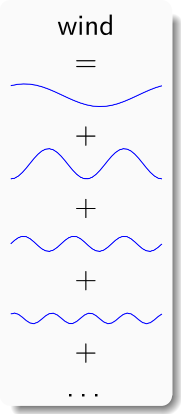
escala espacial L

- spectra for each grid point i
  - longitudinal $S_{ii,u} = \frac{\sigma_u^2 4L_u/\bar{u}}{(1+6fL_u/\bar{u})^{5/3}}$
  - lateral $S_{ii,v} = \frac{\sigma_v^2 4L_v/\bar{u}}{(1+6fL_v/\bar{u})^{5/3}}$
  - vertical $S_{ii,w} = \frac{\sigma_w^2 4L_w/\bar{u}}{(1+6fL_w/\bar{u})^{5/3}}$
- longitudinal coherence between point i and j:

$$\gamma_{ij,u} = \exp\left(-12\sqrt{\left(\frac{f}{\bar{u}}\right)^2 + \left(\frac{0.12}{L_u}\right)^2}\, r_{ij}\right)$$

r_ij distancia entre puntos
solo se relaciona la componente u

Turbulent Wind Field Generation



Wind components without correlation to other points (lateral&vertical IEC Kaimal)

$$v_i(t) = \sum_{m=1}^{n_f} a_m \cos(2\pi f_m t + \theta_{i,m})$$

Amplitudes $a_m = \sqrt{2S_{ii,v}(f_m)\Delta f}$ defined by auto-spectrum $S_{ii,v}$ for each grid point i at frequency f_m and discretization Δf. Also single point longitudinal.

Wind components with correlation to other points (longitudinal IEC Kaimal)

$$u_i(t) = \bar{u} + \sum_{k=1}^{i} \sum_{m=1}^{n_f} a_{ik,m} \cos(2\pi f_m t + \theta_{k,m})$$

Amplitudes $a_{ik,m}$ defined by auto-spectra and coherence between point i and k.

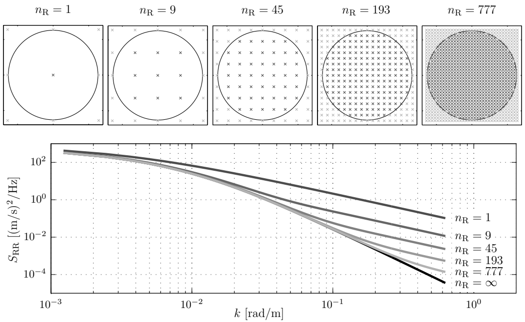
- Wind is “just” a sum of randomly shifted sinusoids with defined amplitudes.
- This method is called the Sandia Method or Veers method [5].

Spectrum rotor effective wind speed

Auto-spectrum of $v_0 = \frac{1}{n}\sum_{i=1}^{n} u_i$

$$
\begin{aligned}
S_{\mathrm{RR}} &= \mathcal{F}\{v_0\}\mathcal{F}^*\{v_0\} \\
&= \frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}\underbrace{\mathcal{F}\{u_i\}\,\mathcal{F}^*\{u_j\}}_{S_{ij,u}} \\
&= \frac{S_{ii,u}}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}\gamma_{ij,u}
\end{aligned}
$$

spectra $S_{ii,u}$ and coherence $\gamma_{ij,u}$ from turbulence model, e.g. Kaimal



[2]

Long-term research challenges

Wind Energ. Sci., 1, 1–39, 2016
www.wind-energ-sci.net/1/1/2016/
doi:10.5194/wes-1-1-2016

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WIND ENERGY SCIENCE

Long-term research challenges in wind energy – a research agenda by the European Academy of Wind Energy

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Published: 9 February 2016

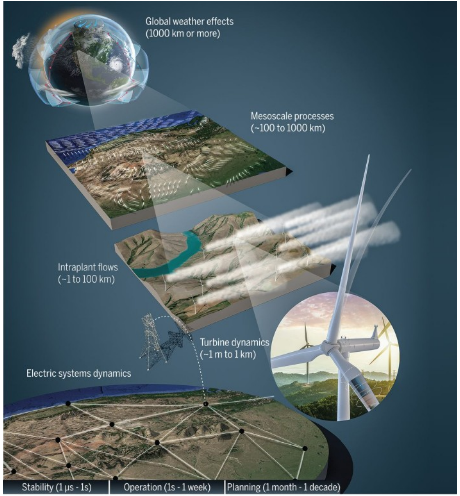
Abstract. The European Academy of Wind Energy (eawe), representing universities and institutes with a significant wind energy programme in 14 countries, has discussed the long-term research challenges in wind energy. In contrast to research agendas addressing short- to medium-term research activities, this eawe document takes a longer-term perspective, addressing the scientific knowledge base that is required to develop wind energy beyond the applications of today and tomorrow. In other words, this long-term research agenda is driven by problems and curiosity, addressing basic research and fundamental knowledge in 11 research areas, ranging from physics and design to environmental and societal aspects. Because of the very nature of this initiative, this document does not intend to be permanent or complete. It shows the vision of the experts of the eawe, but other views may be possible. We sincerely hope that it will spur an even more intensive discussion worldwide within the wind energy community.

[6]

Covered Topics

1. Materials and structures
2. Wind and turbulence
3. Aerodynamics
4. Control and system identification
5. Electricity conversion
6. Reliability and uncertainty modeling
7. Design methods
8. Hydrodynamics, soil characteristics and floating turbines
9. Offshore environmental aspects
10. Wind energy in the electric power system
11. Societal and economic aspects of wind energy

Grand challenges in the science of wind energy 1/2



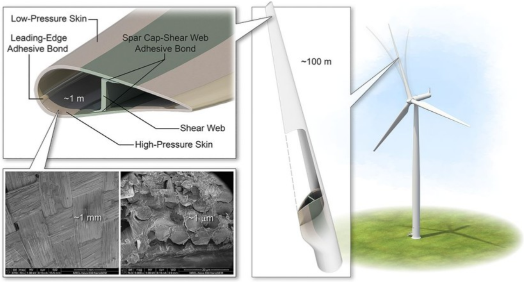
[7]

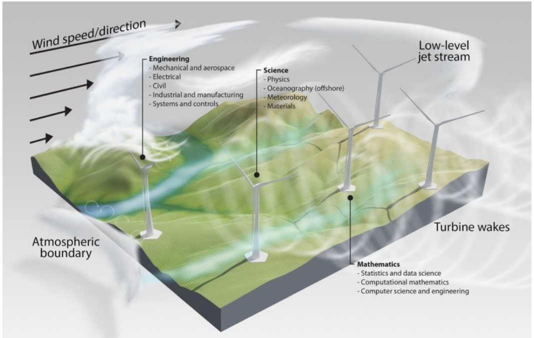
[Video on YouTube]

Main challenges

- mastering the physics of resource from the atmosphere to the intra-plant flows

Grand challenges in the science of wind energy 2/2





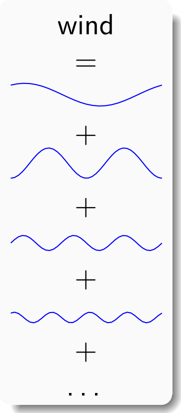
[7]

- characterizing the structural, aero- and hydrodynamics of the largest rotating structures ever built coupled with access to the most advanced materials at commodity prices
- controlling wind power plants to orchestrate wind turbine, plant, and grid formation operations for a stable, resilient, reliable and affordable energy system

Conclusion

Main questions

- How is a turbulent wind field generated?



Sum of randomly shifted sinusoids with defined amplitudes

- lateral, vertical, single point longitudinal IEC Kaimal: amplitudes defined by auto-spectrum, one random phase angle per frequency

$$v_i(t) = \sum_{m=1}^{n_\mathrm{f}} a_m \cos(2\pi f_m t + \theta_{i,m})$$

- longitudinal IEC Kaimal: amplitudes defined by auto-spectrum and coherence, phase angles from previous generated points are included

$$u_i(t) = \bar{u} + \sum_{k=1}^{i} \sum_{m=1}^{n_\mathrm{f}} a_{ik,m} \cos(2\pi f_m t + \theta_{k,m})$$

Quick check on learning objectives

After this lectures you should be able to...

- linearize a reduced turbine model.
- design a PI torque controller.
- describe how the limits and reference values for the torque PI are obtained.
- describe methods how the two PI controller can be coupled.
- generate a time series of longitudinal wind following IEC standard.

References

[1] R. Gasch and J. Twele. *Wind Power Plants : Fundamentals, Design, Construction and Operation*. Springer, 2012. ISBN: 978-3-642-22938-1.

[2] D. Schlipf. "Lidar-Assisted Control Concepts for Wind Turbines". PhD thesis. University of Stuttgart, 2015. DOI: 10.18419/opus-8796.

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Please let me know if you have further questions!

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