New Turbine Control Upgrades Arising From Converging Beam LIDAR Research

Dr Theodore Holtom (Wind Farm Analytics) in collaboration with
Dr Anthony Brooms (Birkbeck, Univ. London)

All-Energy Conference

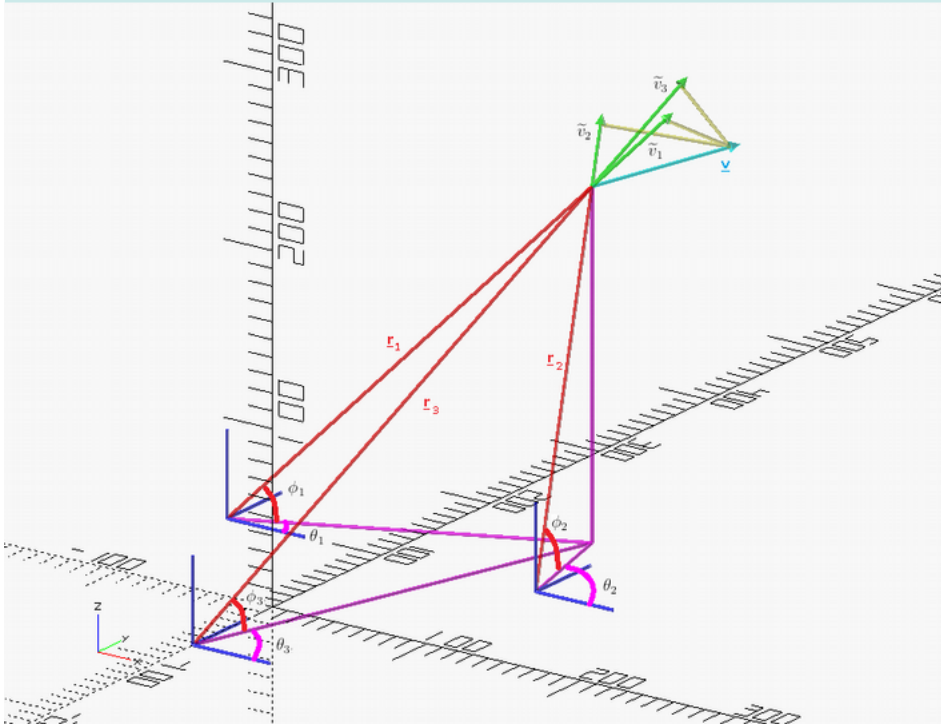
11th May 2023

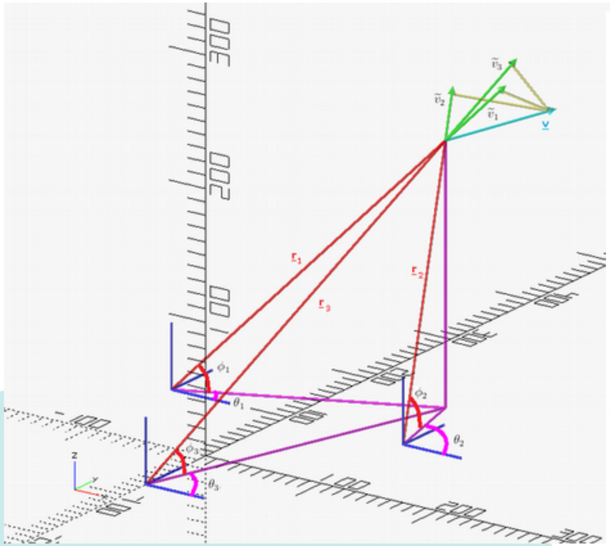
Birkbeck
UNIVERSITY OF LONDON

Wind Farm Analytics

FUNDAMENTALS – WIND IS 3D

- Wind Farm Analytics collaborates with Birkbeck, University of London. Our work is focused around the simple and fundamental fact that wind velocity is a vector with three-dimensional direction as well as magnitude.
- This presentation will highlight how the wind industry has been neglecting this basic physics & geometry => opportunity for improvement!
- Wind Farm Analytics proposes that converging beam LIDAR (laser wind measurement) should be used to measure three-dimensional wind velocity at a point in space.
- But in research it is often the case that work in one area gives rise to inventions in another area; our focus on 3d LIDAR has lead to work on wind turbine control systems.





NON-MATHEMATICAL MESSAGE: to properly measure wind velocity you need three distinct laser beam lines of sight

For each Doppler unit vector $\hat{\mathbf{r}}_i$, $i \in \mathcal{I}$, we may characterize its direction by: $\theta_i \in [0, 2\pi)$, the azimuthal angle measured anti-clockwise from the x-axis; $\phi_i \in [-\pi/2, \pi/2]$, the elevation angle from the (x, y)-plane, taken to be positive when the z-coordinate is positive (as would normally be the case for a platform set on the ground measuring a point that is above ground). Then each of the Doppler unit vectors can be re-expressed in terms of the standard basis as follows:

$$\hat{\mathbf{r}}_i = \cos(\theta_i)\cos(\phi_i)\mathbf{e}_1 + \sin(\theta_i)\cos(\phi_i)\mathbf{e}_2 + \sin(\phi_i)\mathbf{e}_3 \quad i \in \mathcal{I}. \tag{3}$$

Equations (2) and (3) can also be written in matrix form:

$$\tilde{\mathbf{v}} = \mathbf{M}\mathbf{v} \tag{4}$$

where

$$\mathbf{M}_{i1} = r_{i1} = \cos(\theta_i)\cos(\phi_i), \quad i \in \mathcal{I} \tag{5}$$

$$\mathbf{M}_{i2} = r_{i2} = \sin(\theta_i)\cos(\phi_i), \quad i \in \mathcal{I} \tag{6}$$

$$\mathbf{M}_{i3} = r_{i3} = \sin(\phi_i), \quad i \in \mathcal{I} \tag{7}$$

and

$$\tilde{v}_i = \sum_{j \in \mathcal{I}} \mathbf{M}_{ij} v_j = \cos(\theta_i)\cos(\phi_i)v_1 + \sin(\theta_i)\cos(\phi_i)v_2 + \sin(\phi_i)v_3, \quad i \in \mathcal{I}. \tag{8}$$

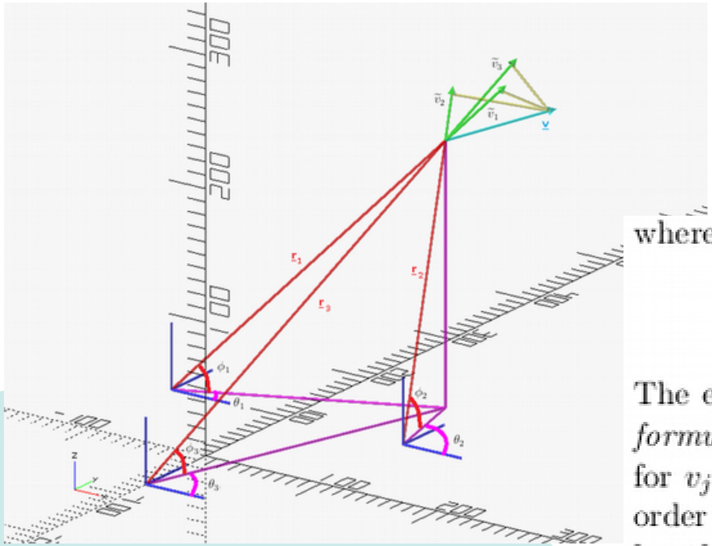
It will be assumed throughout the remainder of this paper that $\mathbf{M}$ *is of full rank.*

Thus, given the 6 Doppler angles and the 3 Doppler wind velocity coordinates, one can determine the equivalent co-ordinate representation of the wind velocity with respect to the standard basis:

$$\mathbf{v} = \mathbf{M}^{-1}\tilde{\mathbf{v}} \tag{9}$$

or, equivalently,

$$v_j = \sum_{k \in \mathcal{I}} [\mathbf{M}^{-1}]_{jk} \tilde{v}_k \quad j \in \mathcal{I}. \tag{10}$$



NON-MATHEMATICAL MESSAGE: we study wind measurement uncertainty because this determines financial uncertainty in planning and also allows better wind turbine optimisation!

where

$$s^2_{v_j}(\boldsymbol{\theta}_0, \boldsymbol{\phi}_0, \tilde{\mathbf{v}}_0) = \sum_{n \in \mathcal{I}} \left\{ \left(\frac{\partial v_j}{\partial \theta_n}\right)^2 \sigma^2_{\theta_n} + \left(\frac{\partial v_j}{\partial \phi_n}\right)^2 \sigma^2_{\phi_n} + \left(\frac{\partial v_j}{\partial \tilde{v}_n}\right)^2 \sigma^2_{\tilde{v}_n} \right\} \Bigg|_{(\boldsymbol{\theta}_0, \boldsymbol{\phi}_0, \tilde{\mathbf{v}}_0)} . \tag{17}$$

The expression for $s^2_{v_j}(\boldsymbol{\theta}_0, \boldsymbol{\phi}_0, \tilde{\mathbf{v}}_0)$ corresponds to the standard expression for the *error propagation formula* (c.f. Taylor (1997)): typically, formulae such as these are derived by truncating the expression for $v_j(\boldsymbol{\theta}^*, \boldsymbol{\phi}^*, \tilde{\mathbf{v}}^*)$ at first order and finding the variance of just that, without actually taking higher order terms into account, unlike our account of the result. **The calculation of $s^2_{v_j}(\boldsymbol{\theta}_0, \boldsymbol{\phi}_0, \tilde{\mathbf{v}}_0)$ will be the focus of our discussion for the remainder of this paper.**

Along with the values of the variances of the six angles and those of the three measured Doppler velocity components, it is also required to evaluate the partial derivatives that appear in (17).

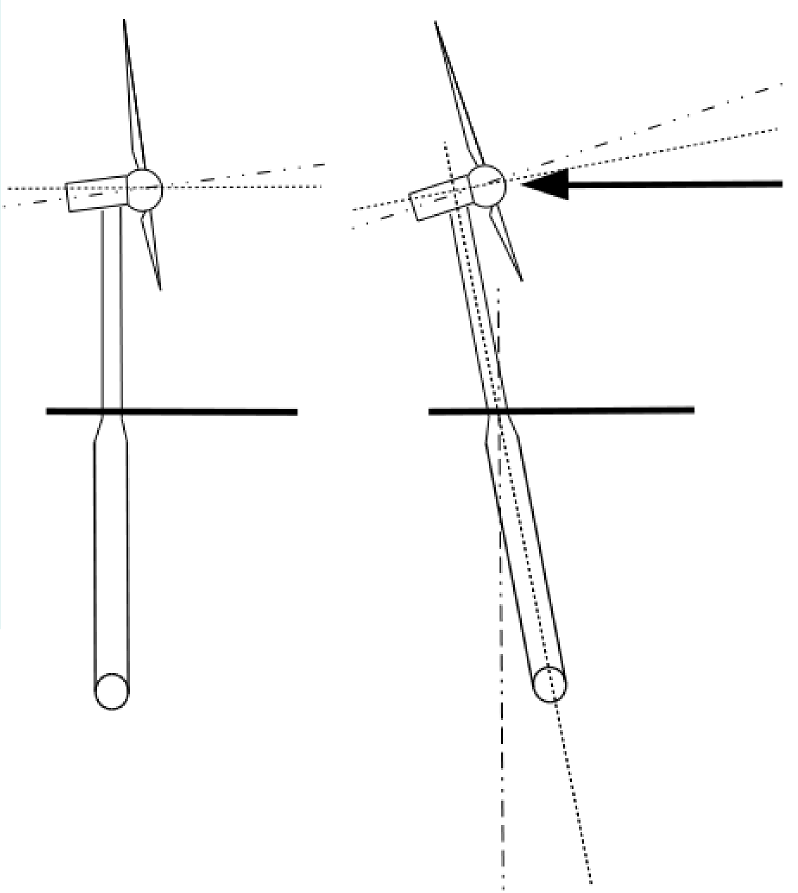
$$\frac{\partial v_j}{\partial \theta_s} = \sum_{k \in \mathcal{I}} \frac{\partial \{[\mathbf{M}^{-1}]_{jk} \tilde{v}_k\}}{\partial \theta_s} = \sum_{k \in \mathcal{I}} \tilde{v}_k \frac{\partial [\mathbf{M}^{-1}]_{jk}}{\partial \theta_s} + \sum_{k \in \mathcal{I}} [\mathbf{M}^{-1}]_{jk} \frac{\partial \tilde{v}_k}{\partial \theta_s} \tag{18}$$

$$\frac{\partial v_j}{\partial \phi_s} = \sum_{k \in \mathcal{I}} \frac{\partial \{[\mathbf{M}^{-1}]_{jk} \tilde{v}_k\}}{\partial \phi_s} = \sum_{k \in \mathcal{I}} \tilde{v}_k \frac{\partial [\mathbf{M}^{-1}]_{jk}}{\partial \phi_s} + \sum_{k \in \mathcal{I}} [\mathbf{M}^{-1}]_{jk} \frac{\partial \tilde{v}_k}{\partial \phi_s} \tag{19}$$

$$\frac{\partial v_j}{\partial \tilde{v}_s} = \sum_{k \in \mathcal{I}} [\mathbf{M}^{-1}]_{jk} \frac{\partial \tilde{v}_k}{\partial \tilde{v}_s} = \sum_{k \in \mathcal{I}} [\mathbf{M}^{-1}]_{jk} \delta_{sk} \tag{20}$$

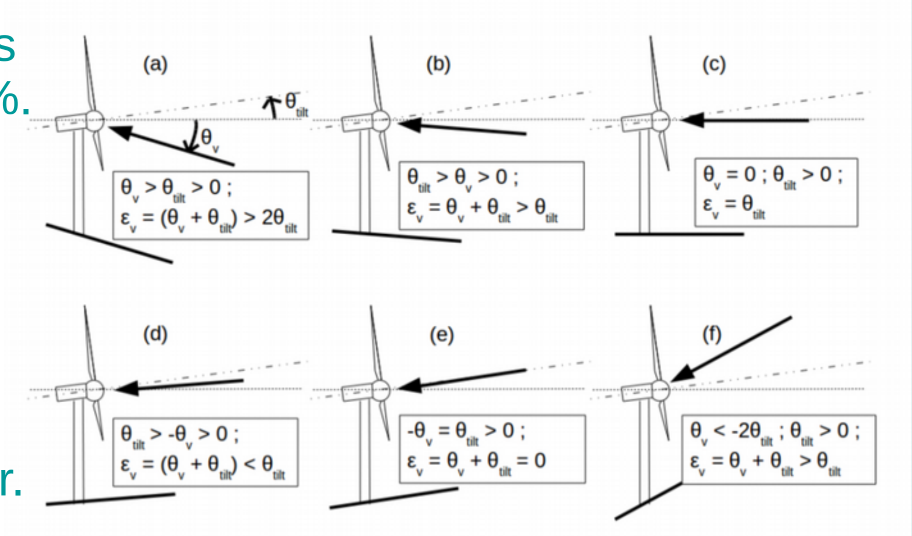
FLOATING ONSHORE(!) TURBINES

- Floating offshore wind turbines are very similar to onshore wind turbines mounted on a floating foundation.
- This presentation will discuss how onshore wind operational learning can be applied to floating turbines.
- The industrial “horizontal axis wind turbine” has its rotor plane tilted (typically 5°) to the vertical and therefore its rotor axis tilted (typically 5°) to the horizontal.
- This design feature has reason to avoid blades flexing to the extent that they strike the tower and kill the ‘mill.
- But modern industrial turbines are axial flow turbines and any angular misalignment between wind flow and rotor axis introduces inefficiency.
- For floating turbines flow misalignment may be made worse by thrust force tilting the turbine back in the water.



NON-HORIZONTAL FLOW LOSSES

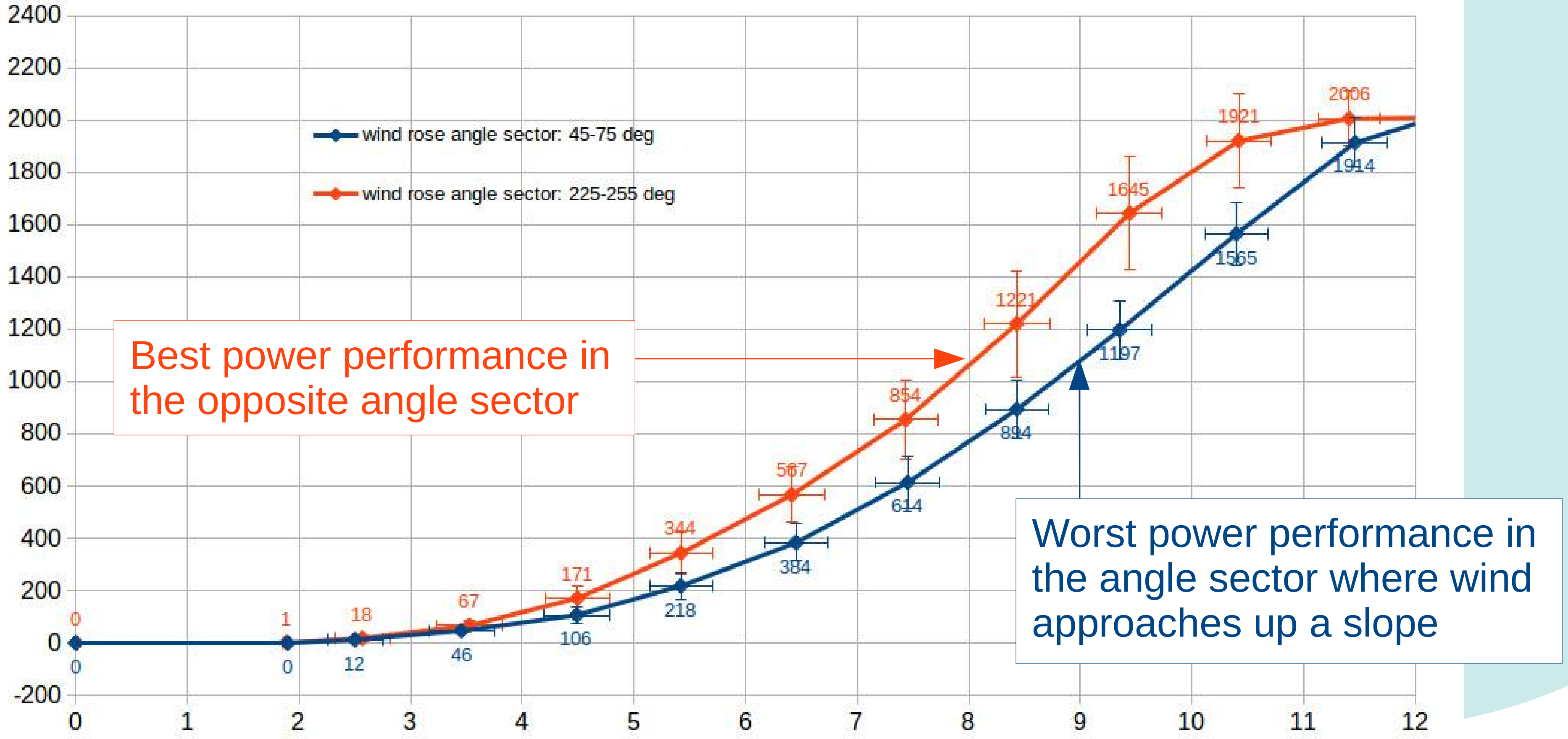
- Onshore wind farms in hilly locations produce similar conditions to floating turbines!
- Roughly speaking the wind follows terrain, sometimes even favourably wrt rotor axis [Fig.(e)].
- Turbines witness varying angular flow misalignments according to horizontal wind direction.
- Operational data analysis shows quite gentle slopes give rise to significant production losses such as 5%.
- Often the slopes can lead to ~10% production losses worth typically £1 million or more per UK 2MW turbine with 20 years lifetime.
- For larger turbines (eg 4+ MW) losses are greater.
- For longer lifetimes (eg 30 years) losses are greater.
- This is the vertical equivalent of running turbines with a permanent horizontal yaw error/misalignment.



HOW DO WE KNOW THIS?

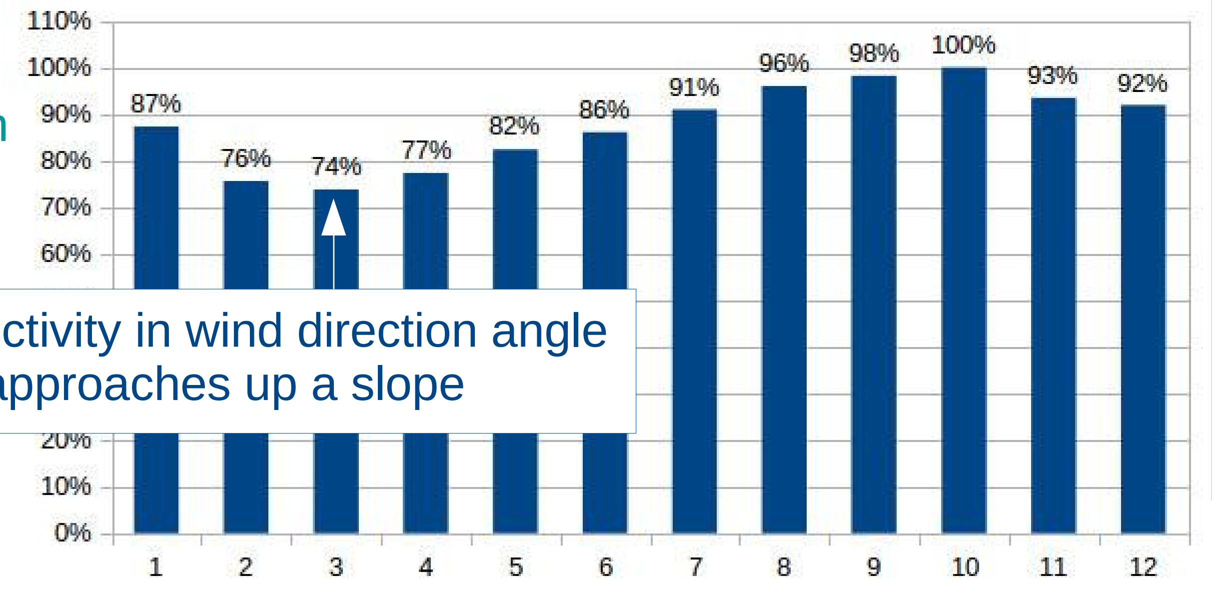
- It is easy to prove and quantify this per (hilly WF) turbine once we have operational data.
- We simply split the power curve data into 12x (horizontal) 30° wind direction sectors.
- We can then compare power performance in each sector, each with its own terrain slope.
- However, the interesting thing is that we see many turbines where the minimum performance is exactly when the wind is coming up a slope underneath the turbine.
- This can be understood because the turbine rotor axis is typically tilted upward ~5°.
- When wind flows up a slope under the turbine then axis tilt increases the misalignment.
- There are many possible reasons for under-performance but if repeatable worst performance is when wind comes up the slope, then in the absence of other explanations, you can be confident the DOMINANT cause of losses is vertical flow inclination.

POWER CURVE PROOF



QUANTIFY LOSSES PER TURBINE

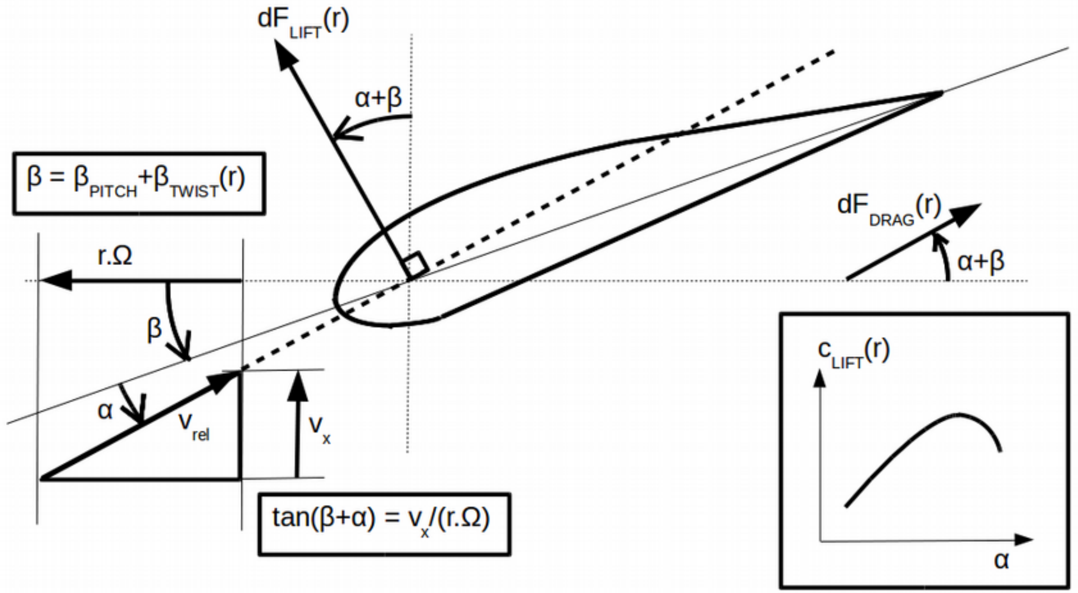
- Its easy to convert power curve into productivity per (12x) 30° wind direction/yaw sector.
- For turbines on a consistent slope it is common to see a sinusoidal wave effect with the lowest productivity when the wind flows uphill and the best productivity in opposite sector.
- Some people questioned whether its due to wakes but wake sectors were calculated and found to be insignificant.
- Note: some turbines exhibit a more complicated picture due to the terrain being very complicated.



Worst energy productivity in wind direction angle sector where wind approaches up a slope

EXPLANATION: AERODYNAMICS

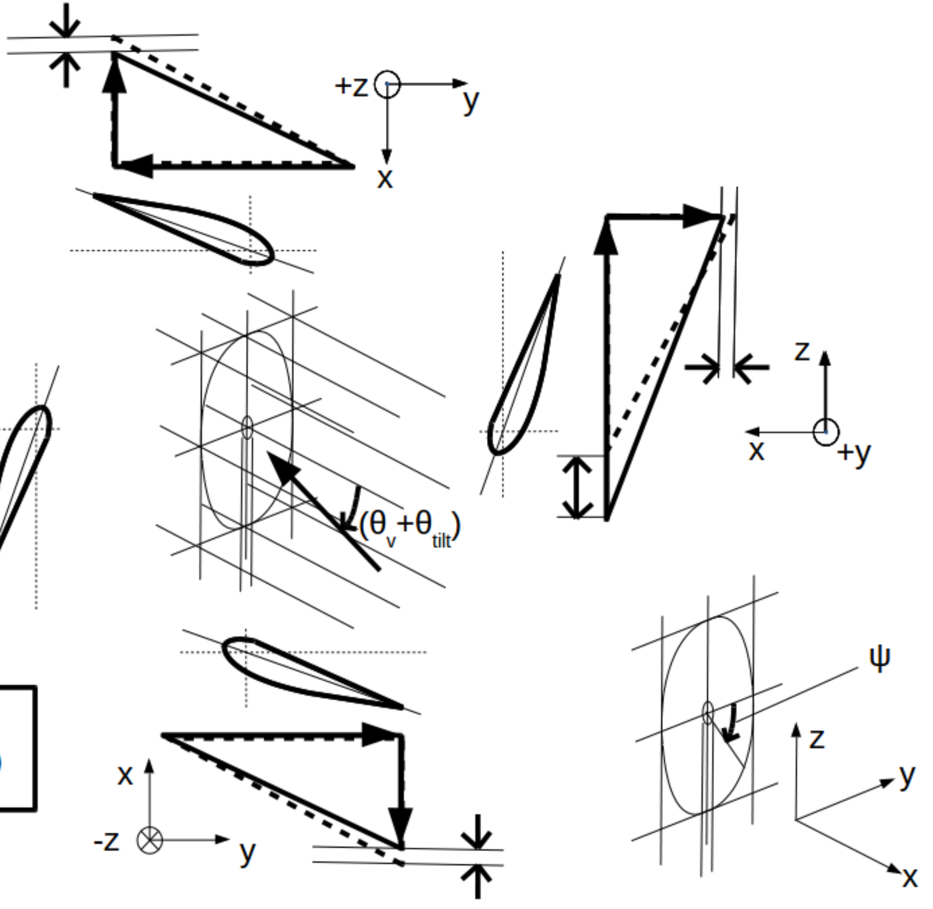
- Imagine you are an elf with x-ray vision sitting on the tip of the blade and looking toward the rotor centre!
- Focusing on a blade element around halfway along the blade you notice...
- The blade element speed within rotor plane (r.Ω) may be greater than <u>axial</u> wind speed (v_x) driving the turbine.
- These perpendicular airspeed components form a velocity triangle which defines the aerodynamic angle of attack, α (and therefore lift force).
- Note: Turbine controller uses blade pitch motor control (β) to govern α.

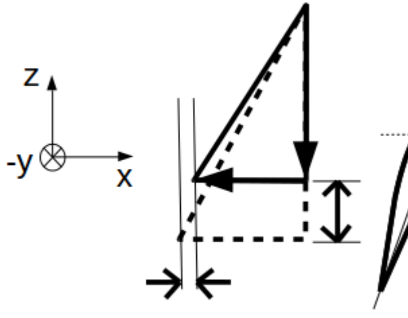


MORE:

- The key thing to notice is that when wind flows up a slope then the velocity triangle varies cyclically as the blade travels around the rotor.
- When blade travels down (RHS) the relative airspeed is increased in the rotor plane and when the blade travels up (on LHS) this airspeed is decreased.
- The cyclic change in this triangle means the angle of attack has a cyclic error which causes loss of lift.

$$\begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} = \begin{pmatrix} v.\cos(\theta_v+\theta_{tilt}) \\ 0 \\ v.\sin(\theta_v+\theta_{tilt}) \end{pmatrix}$$





$$\tan(\beta+\alpha) = (v.\cos(\theta_v+\theta_{tilt}))/(r.\Omega + v.\sin(\theta_v+\theta_{tilt}).\cos\psi)$$

WHAT CAN WE DO ABOUT IT?

- For hilly wind farms steep slopes should be avoided in favour of less steep slopes during planning and development. You wouldn’t run your turbine deliberately with an avoidable horizontal yaw error so why would you allow equivalent misalignment in the vertical plane?
- However many sites may be unavoidably hilly and the developer naturally wants as many (anyway profitable) wind turbines as possible for maximising green revenue.
- But if we can get significantly more wind energy at low cost then its logical to do so. The good news is that where there is a cyclic error on the aerodynamic angle of attack we can correct it using an opposite cyclic adjustment with the blade pitch control systems.
- The same solution can be applied to floating turbines and it could be worth even more!
- This can add value during planning of wind farms, or by upgrade / retrofit of existing turbines.
- Upgrade can be achieved by working with turbine suppliers, or via independent specialists.
- Tune up your wind turbine performance parameters like a racing car!

FLOATING APPLICATION

- We can obtain similar percentage gains for floating turbine as with hilly onshore turbines for the simple geometric reason that floating tilt angle is of similar magnitude as terrain angles.
- But bigger turbines, higher capacity factors, and the fact that flow misalignment is present for all wind directions (unlike hilly wind turbine locations where it is reduced for some wind directions) we can expect the monetary value to be much higher for floating turbines.
- Additional to (a) the thrust force causing increasing tilt with increasing wind speed, there are (b) variations and oscillations in tilt angle due to variable wind and variable wave motion.
- It is noted that increased average wind speed is a main reason to deploy floating turbines.
- ...and that increased wind speed is often associated with increased wave motion (incl. tilt).
- Mathematically we can account for the full 6 DOF motion (roll, pitch/”tilt”, yaw, surge, heave sway) of the floating foundation. Operationally these parameters can be supplied by sensors.
- Motion will vary according to different foundation designs and different deployment conditions but we can account for all possibilities. Lets make this global improvement!

INDUSTRY FEEDBACK (more available)

- Director, UK Wind Farm Owner/Developer: "[WFA is] speaking common sense, owners would be ready to do profit sharing deals with turbine manufacturers";
- World Leading Control Specialist, Certification Provider: "[WFA is] quite right - pitch control can be used to compensate for change in aerodynamic angle of attack";
- Senior Expert in Loads and Optimisation, Major EU Wind Turbine Manufacturer: "[WFA] idea is quite interesting";
- Control Engineer, EU Control Specialist: "we like the idea, see potential, have successfully checked it with computer simulations and are now working on implementation at a multi-MW turbine";
- Loads & Measurement Engineer, EU Wind Turbine Manufacturer: "Maths and physics is clear - we see the potential";
- Aerodynamic Engineer, EU Blade Specialist: "totally convinced, it totally makes sense";
- CTO, EU/Chinese Wind Technology Co: "The [WFA] method can work and has potential for handling combinations of shear, yaw, upflow, etc";

COMMERCIAL OPPORTUNITIES

- Wind turbine buyers are ready to do profit sharing deals with turbine suppliers.
- There is an avalanche of customer opportunity waiting to be triggered.
- Wind turbine manufacturers can obtain competitive advantage by offering this option.
- This option can open up new markets (such as in steep terrain).
- The blade pitch motor methods can be beneficially applied to floating offshore turbines.
- Wind turbine certification limits can be broadened to a larger operational envelope.
- LIDAR manufacturers can offer new services.
- Wind farm developers obtain option to add value to their projects during the planning stage.
- Automatic SCADA data processing can identify lead upgrade candidates and quantify value.
- Automatic data processing can identify upgrade candidates and value during planning.

INNOVATION PARTNERSHIP?

- Wind farm Analytics is ready to join existing or new research/demonstration collaborations to demonstrate and study this opportunity in the context of floating wind turbines.
- In cases where floating, offshore or onshore wind farm consent process favours inclusion of innovation then we can certainly offer that.
- Optionally we are ready to work with floating foundation providers on given design application.
- Optionally we are ready to work with turbine suppliers on developing the new commercial and technical options which we have discovered.
- Optionally we are ready to work with turbine suppliers, developers and owners to automate calculation of upgrade value per turbine and automate calculation of upgrade parameters.
- Optionally we are ready to work also with existing LIDAR suppliers to obtain further gains by use of this pitch control method including also LIDAR data.
- Optionally we are ready to expand our academic collaboration (Birkbeck, Univ. of London)

CONCLUSIONS

- The wind industry does not pay sufficient attention to non-axial wind flow.
- This is seen from many met masts still employing instruments measuring only horizontal wind speed and direction (eg spinning cups). 3D converging beam LIDAR would be better.
- By taking 3D flow into account there is opportunity to increase asset energy yield and value.
- For many wind turbines in hilly situations this could be worth up to 10% of energy production.
- We can earn ~£1 million or more extra per onshore hilly turbine lifetime at cost of software update. This can be even more valuable for large floating turbines!
- Further advantages include load/vibration reduction, leading to less failures in operation, reduction of downtime/maintenance costs and increasing overall asset lifetime.
- Wind Farm Analytics Ltd has patented a family of related control methods.
- Wind Farm Analytics Ltd seeks partners and/or investors for demonstration & global roll-out.

Dr Theodore Holtom
+44 7720 767545
info@wind-farm-analytics.co.uk