# Wake Steering Optimisation using FLORIS

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# Introduction

Wind turbines create wakes behind them during operation which can extend to several rotor diameters. Flow within the wake is characterized by decrease in wind speed (known as wake deficit) and increase in turbulence (Larsen et al.,2008) [1]. Wakes affect the performance of downstream turbines caught in the wake of the upstream turbines. There is a significant power reduction(around 40% power loss) and  increased structural loading for turbines operating within a wake region (Akbar et al.,2015) [2]. Several control strategies exist in literature that can mitigate the effects of wake. One approach is to steer the wakes through yaw-misalignment or tilting. Another common method is axial induction control. The focus of this project is on the wake steering through yaw-misalignment.

Figure 1. Natural visualization of wakes

# Wake Physics

## Wake Models

Wakes are modeled using analytical equations that are developed based on results of experiments and simulation along with the understanding of wake physics. Wake models based on analytical equations are computationally cheaper and faster compared to (Computational Fluid Dynamics) CFD. These wake models are fast enough to be used in real time optimization of wind farms. The wake models that exist in literature are Jensen, Multi-zone, Gaussian, Curl, Jimenez and Bastankhah.

### Jensen model

Jensen model is one of the simplest models that exist in literature yet it produces a good estimation of the power output when the wakes are completely overlapped. This model assumes a steady and uniform flow field within the wake. Also, it assumes a linear expansion rate of the wake in the downstream direction [3]. The analytical expression for the Jensen wake model is given by,

$$u(x, r, a) = U_{\infty}(1 - \delta u(x, r, a))$$

where the velocity deficit, $\delta u$ is given by,

$$\delta u = \begin{cases} 2a\left(\frac{D}{D+2kx}\right)^2, & \text{if} \quad r \leq \frac{D+2kx}{2}. \\ 0, & \text{otherwise.} \end{cases}$$

where $U_{\infty}$ is the upstream wind velocity and D is the rotor diameter, x is the downstream distance and k is the wake decay constant, r is the radial distance from rotor center. Value of k

decides the wake expansion rate and recovery rate. The k value is dependent on the ambient turbulent intensity, turbine operation and topographical effects. and typically ranges from 0.01 to 0.5. The Jensen wake model does not conserve momentum or take into account the added turbulence due to turbine operation (Jennifer Annoni et al.,2018) [3].

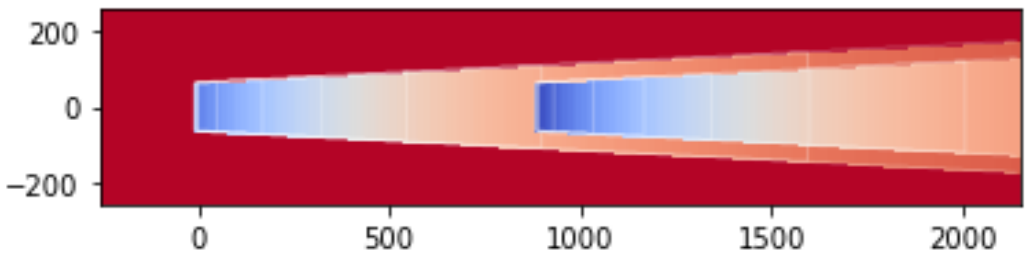



Figure. 2 Horizontal cut section of wake profile calculated with Jensen model

## Multi-Zone model

Multi-zone model is a modified version of the Jensen model. It considers the effect of partial wake overlapping which is observed in yawed conditions. In this model, wake zone is divided into 3 zones as follows 1) near wake zone 2) far-wake zone 3) mixing-wake zone. This model shares some of the same limitations of Jensen wake model like it does not conserve momentum and it doesn't consider the effect of added turbulence (Jennifer Annoni et al.,2018) [3].

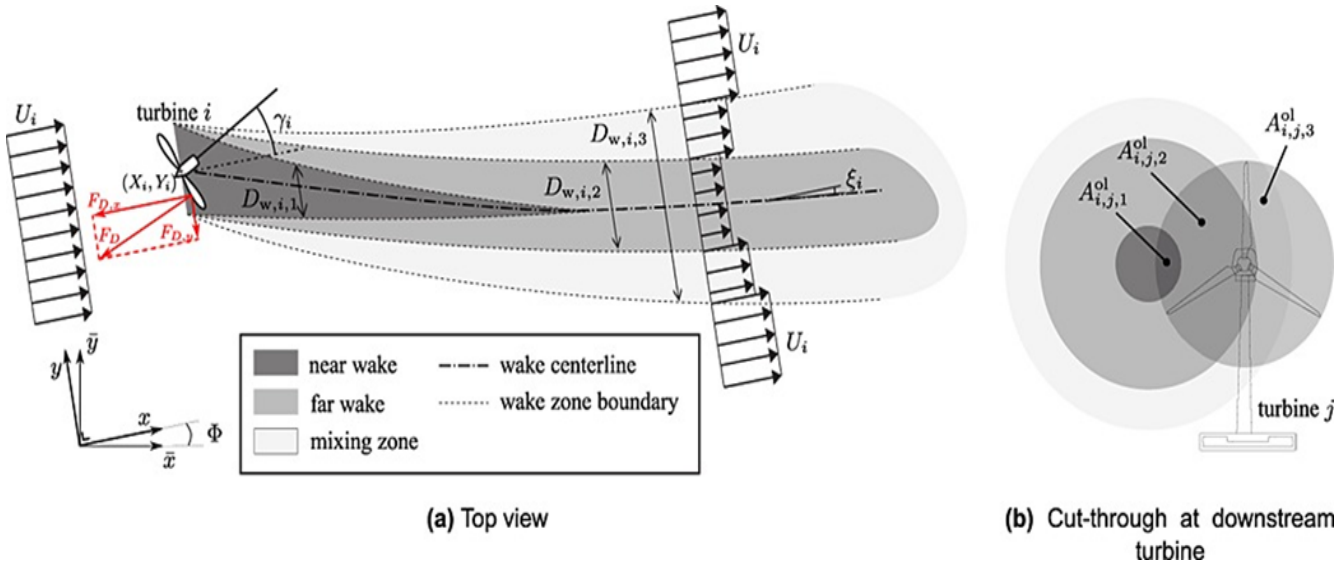



Figure. 3 a) Three different wake zones b) Partial overlap of wakes with downstream turbine

## Gaussian wake model

Gaussian wake models are implemented with FLORIS to evaluate wake profile distribution. This wake model includes velocity deficit, added turbulence (operated wind turbine operations and ambient wind conditions) and atmospheric stability [3]. Linear momentum is conserved, while it has 6 tuning parameters and the model follows linear wake expansion [3].

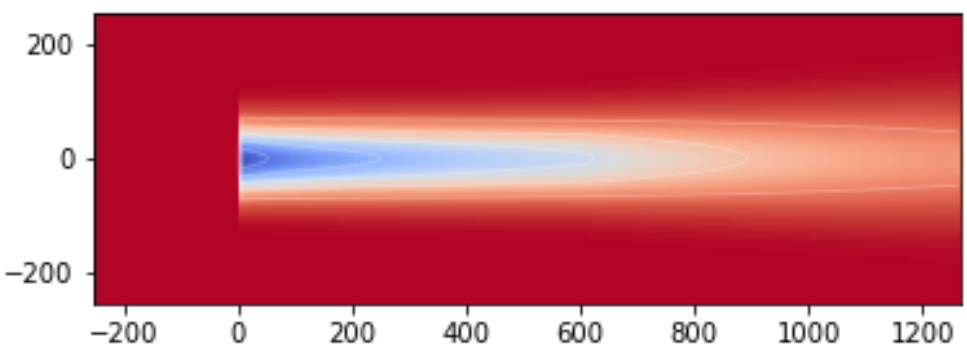



Figure. 4 Wake profile for wind turbine from Gaussian wake model via FLORIS

**1. Velocity Deficit**

The analytical expression for velocity deficit produced by the upstream turbine is calculated from simplified Navier Stokes Equation as [3],

$$\frac{u(x,y,z)}{U_\infty} = 1 - Ce^{-(y-\delta)^2/2\sigma_y^2} e^{-(z-z_\mathrm{h})^2/2\sigma_z^2} \qquad \begin{aligned} C &= 1 - \sqrt{1 - \frac{(\sigma_{y0}\sigma_{z0})M_0}{\sigma_y\sigma_z}} \\ M_0 &= C_0(2 - C_0) \\ C_0 &= 1 - \sqrt{1 - C_\mathrm{T}}, \end{aligned}$$

$C$ : velocity deficit at the wake center, $\delta$ : wake deflection, $z$h : hub height of the turbine , $\sigma y$ : wake width in the $y$ direction, $\sigma z$ : wake width in the $z$ direction, $C$t : thrust coefficient.

**2. Atmospheric stability**

The gaussian model accounts for realistic atmospheric stability parameters like wind veer, wind shear and added turbulence. These parameter values are available from field measurements which can serve as input to the gaussian model to simulate wake profiles. According to Stull [4], the model doesn't account for temperature and flux variation for full representation of atmospheric stability characterizing.

**2.1 Wind Shear**

The 3D model of wake includes wind shear variation with log law for wind [3],

$$\frac{U_\mathrm{init}}{U_\infty} = \left(\frac{z}{z_\mathrm{hub}}\right)^{\alpha_\mathrm{s}},$$

$\alpha$s : shear coefficient, $U$init : initial flow field. A high shear coefficient, $\alpha$s>0.2, is typically used for stable conditions and a low shear coefficient, $\alpha$s<0.2 [4].

**2.2 Wind Veer**

The wind direction varies along the rotor diameter of the wind turbine known as wind veer. The wind veer rotation are imparted to the Gaussian wake models, given by the analytical expression as [3],

$$\frac{u(x,y,z)}{U_{\text{init}}} = 1 - Ce^{-(a(y-\delta)^2 - 2b(y-\delta)(z-z_{\text{hub}}) + c(z-z_{\text{hub}})^2)}$$

$$a = \frac{\cos^2\phi}{2\sigma_y^2} + \frac{\sin^2\phi}{2\sigma_z^2} \quad b = -\frac{\sin 2\phi}{4\sigma_y^2} + \frac{\sin 2\phi}{4\sigma_z^2} \quad c = \frac{\sin^2\phi}{2\sigma_y^2} + \frac{\cos^2\phi}{2\sigma_z^2},$$

$\phi$ : amount of veer across rotor & the equation represents a standard Gaussian rotation

**2.3 Added Turbulence**

Wake expansion occurs due to added turbulence from the ambient conditions and during turbine operation. The wake profiles are mapped effectively by the model within 15D (Rotor diameter) distance. The analytical expression for added turbulence is [3],

$N$ : number of turbines influencing the downstream turbines, $I0$ : ambient turbulence intensity, and the added turbulence due to turbine $i$.

$$I = \sqrt{\sum_{j=0}^{N}\left(I_j^+\right)^2 + I_0^2},$$

$$I^+ = A_{\text{overlap}}\left(0.8a_i^{0.73} I_0^{0.35}\left(x/D_i\right)^{-0.32}\right),$$

## Curl wake model

Curl wake model has two counter rotating vortices picturing the wake profiles downstream of the turbine. The set of counter rotating vortices are superposed to obtain an overall curl model across the rotor plane. The model solves the Navier Stokes Equation linearly, with some approximations, to compute the curl wake profiles [5].

$$U\frac{\partial u'}{\partial x} + V\frac{\partial u'}{\partial y} + W\frac{\partial (U+u')}{\partial z} = \nu_{\text{eff}}\left(\frac{\partial^2 u'}{\partial x^2} + \frac{\partial^2 u'}{\partial y^2} + \frac{\partial^2 u'}{\partial z^2}\right).$$

$\nu$eff : effective (turbulent and molecular) viscosity

The linearized Euler momentum equation is solved from the rotor plane upto the downstream turbine [6]. This model takes a larger computational time about (1-10 sec) [6] but accurately represents the bean shaped profile of the wake. It was developed in 2019 and has been incorporated into the FLORIS framework [7].

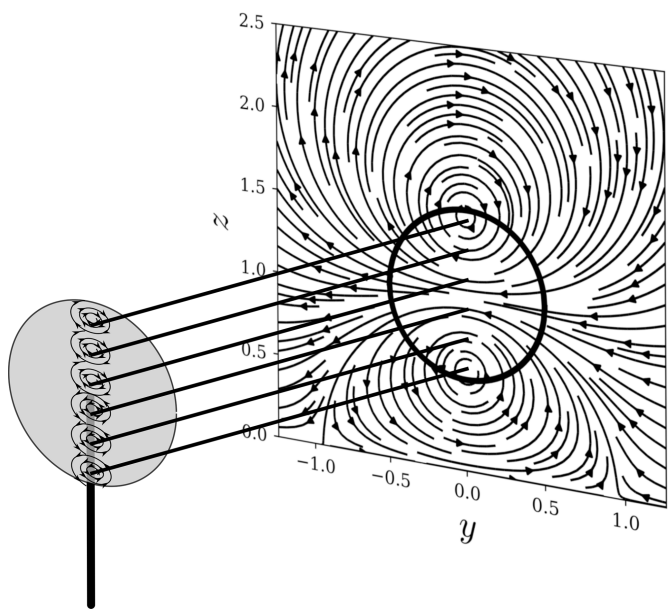
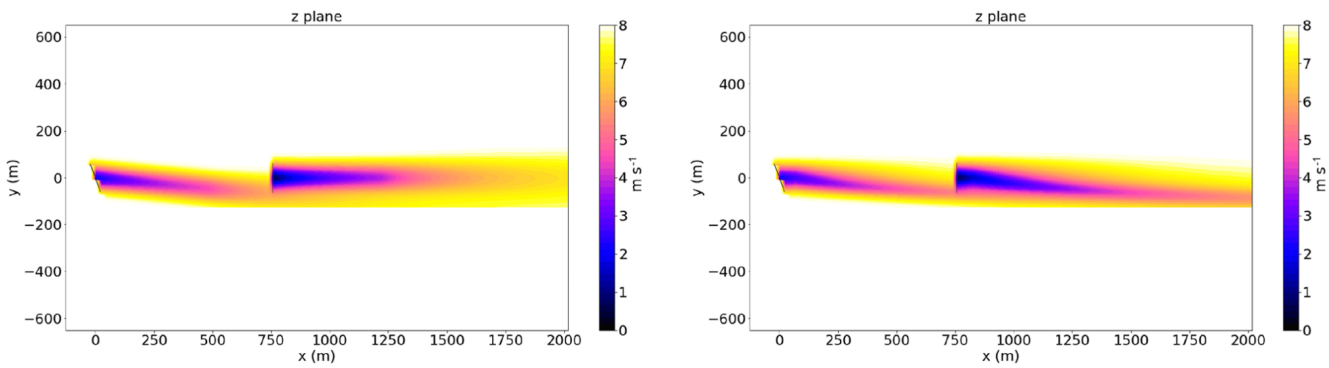



Figure. 5 Superposition of collection of vortices to create curl wake [5]

## Comparison of curl wake and gaussian wake models

Gaussian models assume a fixed elliptical shape of wake for each turbine and have lower computational power than curl wake models. While, curl wake models accurately map the bean shaped curl wakes with more computational time and wakes can take any shapes [5].




(a) Gaussian model

(b) Curled wake model

Figure. 6 Wake Steering and shape comparison for Gaussian and Curl wake models [5]

# Wake deflection models

Wake deflection models predict the deflection of wake when turbines are yawed. The deflection models include Jimenez and Bastankhah models.

## A. Wake asymmetry

Positive and negative yaw angles do not produce the same amount of wake deflection. This effect can be explained by considering the counter-generating vortices that are shed by the yawed turbine in the upper and lower half of the rotor plane. The asymmetry is caused by the interaction of these vortices with the rotating wake in the direction of rotor blade rotation (Jennifer Annoni et al.,2018) [3].

## B. Secondary steering

Deflected wakes can steer the wakes of downstream turbines even if the downstream turbines are not yawed. This effect is again caused when the counter-rotating vortices in the deflected wake interact with the downstream turbine wake (Jennifer King et al.,2021) [8].

# FLOw Redirection and Induction in Steady State (FLORIS)

FLOw Redirection and Induction in Steady State (FLORIS) is a wind plant optimization tool developed by NREL and the Delft University of Technology. FLORIS is a Python based open-source platform that can be used to optimize control strategies like wake steering [9].

The tool uses the wake models, deflection models and turbine models to calculate wakes, estimate power outputs and optimize yaw angles for maximizing power output. Furthermore, the gain in Annual energy Production can be calculated when turbines are optimally yawed for different wind conditions. Installation procedure and example codes for FLORIS are provided in the appendix.

## Case Study

For the case study, a 3x3 wind farm layout was chosen with the following parameters. The turbine used here is the NREL 5MW. The Gaussian wake model was used to calculate the wake profiles.

| | Baseline | Case 1 | Case 2 | Case 3 |
|---|---|---|---|---|
| Wind speed | 8 m/s | 8 m/s | 8 m/s | 8 m/s |
| Wind direction | 270° | 270° | 270° | 270° |
| Cut plane height | 90 m (same as hub height) | 90 m (same as hub height) | 90 m (same as hub height) | 90 m (same as hub height) |
| Turbulence intensity | 0.06 | 0.06 | 0.06 | 0.06 |
| Wind turbine spacing | 7D | 8D | 7D | 8D |
| Wind shear | 0.12 | 0.12 | 0.12 | 0.12 |
| Wind veer | 0 | 0 | 0 | 0 |
| Yawed condition | Zero yaw | Zero yaw | Optimal yaw | Optimal yaw |
| Farm power output | 9.05 MW | 9.6 MW | 10.7 MW | 11.11 MW |
| Power Gain | 0.0% | 6.9% | 18.5% | 14.9% |

Table 1. Inputs and outputs of wind farm controls from FLORIS for different cases

| | Position | Yaw angles (in °) | | Power output (in MW) | |
|---|---|---|---|---|---|
| | | Case 2 | Case 3 | Baseline | Case 2 |
| Turbine 0 | [0,0] | 25 | 25 | 1.7 | 1.4 |
| Turbine 1 | [7D,0] | 19.5 | 17.7 | 0.6 | 0.9 |
| Turbine 2 | [14D,0] | 0 | 0 | 0.7 | 1.1 |
| Turbine 3 | [0,250] | 25 | 25 | 1.7 | 1.4 |
| Turbine 4 | [7D,250] | 18.3 | 17.6 | 0.6 | 1 |
| Turbine 5 | [14D,250] | 0 | 0 | 0.7 | 1.1 |
| Turbine 6 | [0,500] | 25 | 24.7 | 1.7 | 1.4 |
| Turbine 7 | [7D,500] | 18 | 16.5 | 0.6 | 1 |
| Turbine 8 | [14D,500] | 0 | 0 | 0.7 | 1.1 |

Table 2. Yaw angles & power outputs of individual turbines for non-yawed (baseline) and yawed cases (case 2)

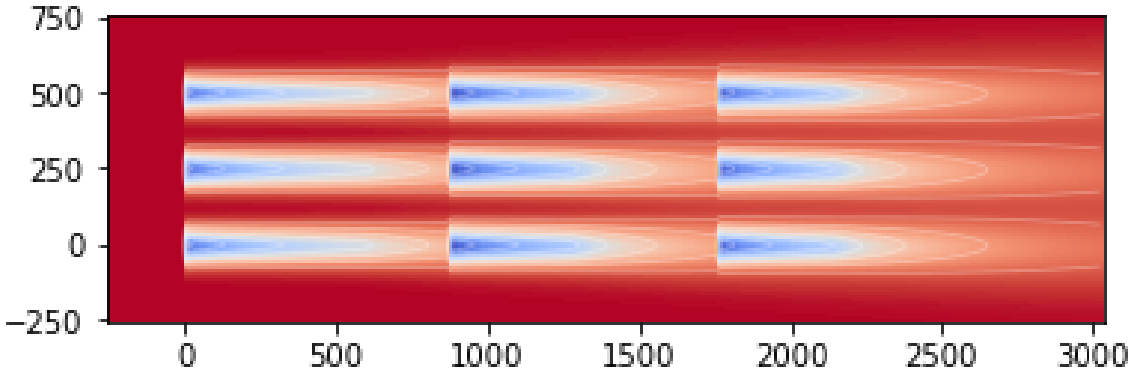



Figure 7. Horizontal cut section of velocity contour at hub height for baseline case

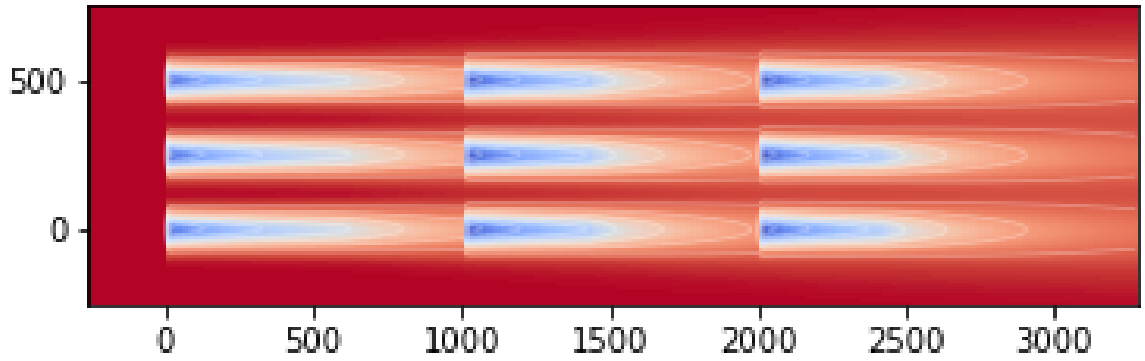



Figure 8. Horizontal cut section of velocity contour at hub height for case 1

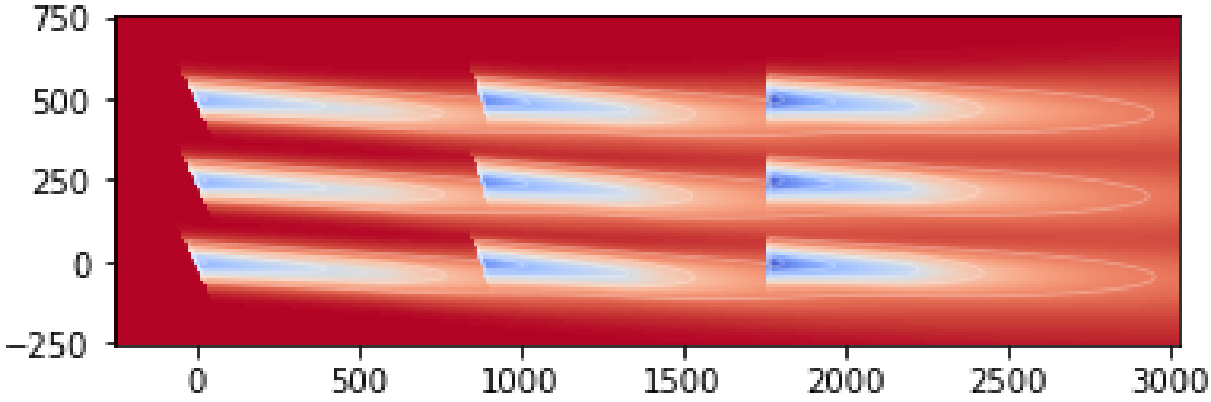



Figure 9. Horizontal cut section of velocity contour at hub height for case 2

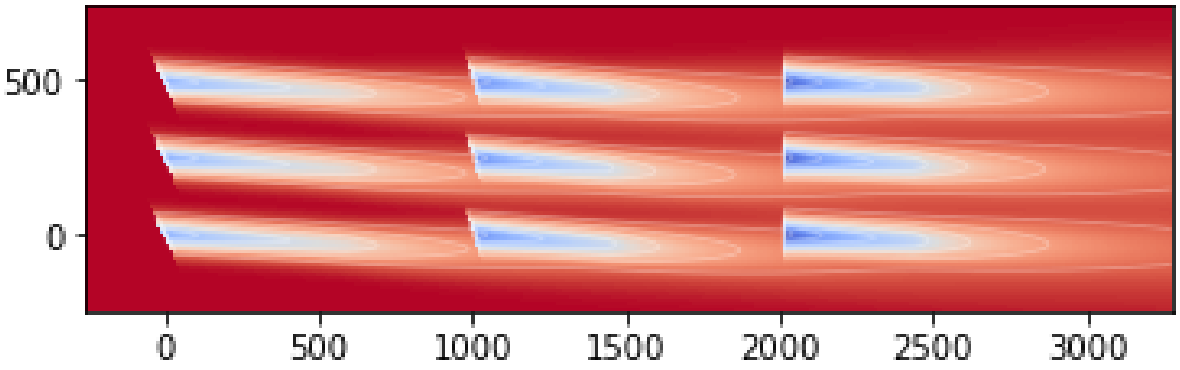



Figure 11. Horizontal cut section of velocity contour at hub height for case 3

Following constraints were used in the optimization -

Minimum yaw angle - 0°  Maximum yaw angle - 25°

The output power is more for 8D due to more turbine spacing allowing wake recovery. It was observed that with increased turbine spacing the power gains from yaw optimization are reduced. For future studies the optimization problem can consider the turbine life when optimizing for maximum power.

**Heterogeneous flow**

Heterogeneous flows are the spatial variation of wind velocities across each turbine rotor .For the same case study, the power output comparison is made for homogenous and heterogenous flows via FLORIS. The Gaussian wake model was used to calculate the wake profiles. In comparison of these two cases, heterogeneous flow wind farm layout had 6.8% more power (from 17235319.56 W to 18405313.37 W) than homogenous flow.

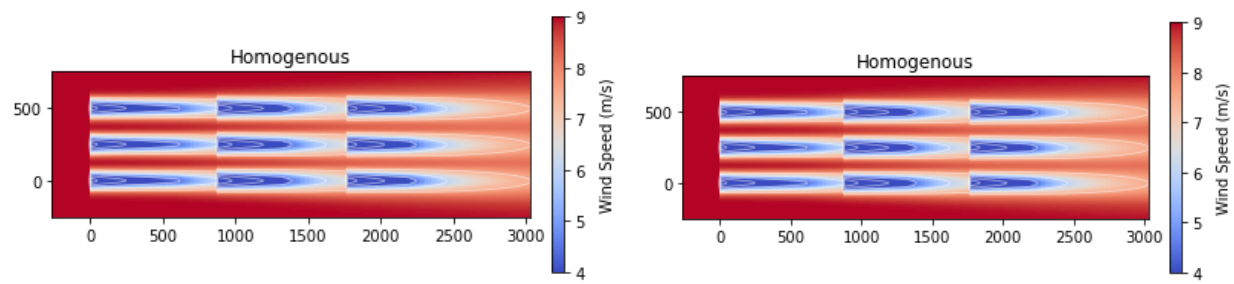



Figure. 12 Homogenous and heterogenous flow for 3x3 Wind farm layout via FLORIS

Table. Optimum yaw angles for heterogeneous 3x3 wind farm turbine

| | Position (in m) | Yaw angles (in °) |
|---|---|---|
| Turbine 0 | [0,0] | 25 |
| Turbine 1 | [7D,0] | 19.99 |
| Turbine 2 | [14D,0] | 0 |
| Turbine 3 | [0,250] | 13.83 |
| Turbine 4 | [7D,250] | 7.421 |
| Turbine 5 | [14D,250] | 2.019 |
| Turbine 6 | [0,500] | 3.66 |
| Turbine 7 | [7D,500] | 1.427 |
| Turbine 8 | [14D,500] | 2.168 |

# Fatigue Life

## Fatigue loads induced via yaw steering

Fatigue loads in turbines are induced when turbines are yawed at an angle. Studies were done by Paul A. Fleming et al. [10], using SOWFA which concluded that for positive angles there were reduced fatigue load values for different turbine components.

The SOWFA results are consistent with experimental fatigue analysis done by Kragh K et. al [11]. However, for negative yaw angles the non- rotating turbine components experienced increased load variation.

Full results of simulations. Turbine wake redirection is summarized by the wake center 7 rotor diameters downstream from the turbine, bold indicates the larger offset.

| | Amount | Horizontal wake-offset abs ($x/D$) | Vertical wake-offset abs ($z/D$) | Power | Blade OOP | Drivetrain | Tower | Yaw bearing |
|---|---|---|---|---|---|---|---|---|
| | Baseline | **0.08** | 0.03 | 0.0% | +0.0% | +0.0% | +0.0% | +0.0% |
| Yaw-Based | −40° | **0.33** | 0.02 | −39.4% | +5.6% | −17.3% | −20.3% | −13.9% |
| | −35° | **0.32** | 0.03 | −31.2% | +8.9% | −10.7% | −17.7% | −0.7% |
| | −30° | **0.27** | 0.00 | −23.8% | +9.5% | −6.1% | −15.2% | −6.7% |
| | −25° | **0.24** | 0.02 | −16.8% | +14.2% | −0.8% | −14.9% | −8.0% |
| | −20° | **0.17** | 0.02 | −11.2% | +11.7% | +2.3% | −7.7% | −9.8% |
| | −15° | **0.10** | 0.02 | −6.0% | +7.2% | +1.5% | −10.5% | −3.5% |
| | −10° | **0.05** | 0.02 | −2.6% | +8.6% | +1.0% | −10.3% | −2.8% |
| | −5° | **0.03** | 0.02 | −0.4% | +5.3% | +0.8% | −5.9% | −3.1% |
| | 5° | **0.17** | 0.05 | −0.3% | −4.0% | −1.6% | −0.1% | −5.1% |
| | 10° | **0.24** | 0.06 | −2.6% | −5.2% | +1.3% | +0.1% | −9.7% |
| | 15° | **0.30** | 0.06 | −5.7% | −9.9% | −0.4% | −3.2% | −11.1% |
| | 20° | **0.35** | 0.05 | −10.6% | −13.3% | −1.0% | −6.0% | −14.4% |
| | 25° | **0.43** | 0.08 | −16.2% | −14.4% | −6.2% | −7.4% | −14.8% |
| | 30° | **0.49** | 0.05 | −23.3% | −17.1% | −10.2% | −12.7% | −8.1% |
| | 35° | **0.51** | 0.05 | −31.3% | −20.1% | −14.9% | −7.9% | −13.5% |
| | 40° | **0.54** | 0.10 | −40.1% | −24.4% | −22.2% | −7.1% | −1.5% |

Table. 3 Fatigue loads values for set of yaw misalignment angles [1]

The fatigue loads calculated are the output power, blade-out-of -plane bending moments, drivetrain torsion, tower side-2-side bending and the yaw and tilting moments experienced by yaw bearing. Thus, yaw steering for positive angles certainly helps in mitigating the structural stresses that may arise [10].

## Fatigue Sustainability through additive manufacturing

Recent advancement in the field of structures has supported the blade able to handle higher fatigue loads. Thereby, enabling them to be yawed with preserving life of turbines.

The picture below depicts a project carried out in collaboration between NREL and Oak Ridge National Lab, where they are testing the fatigue properties of 3 blades, 2 in lab and 1 on field.

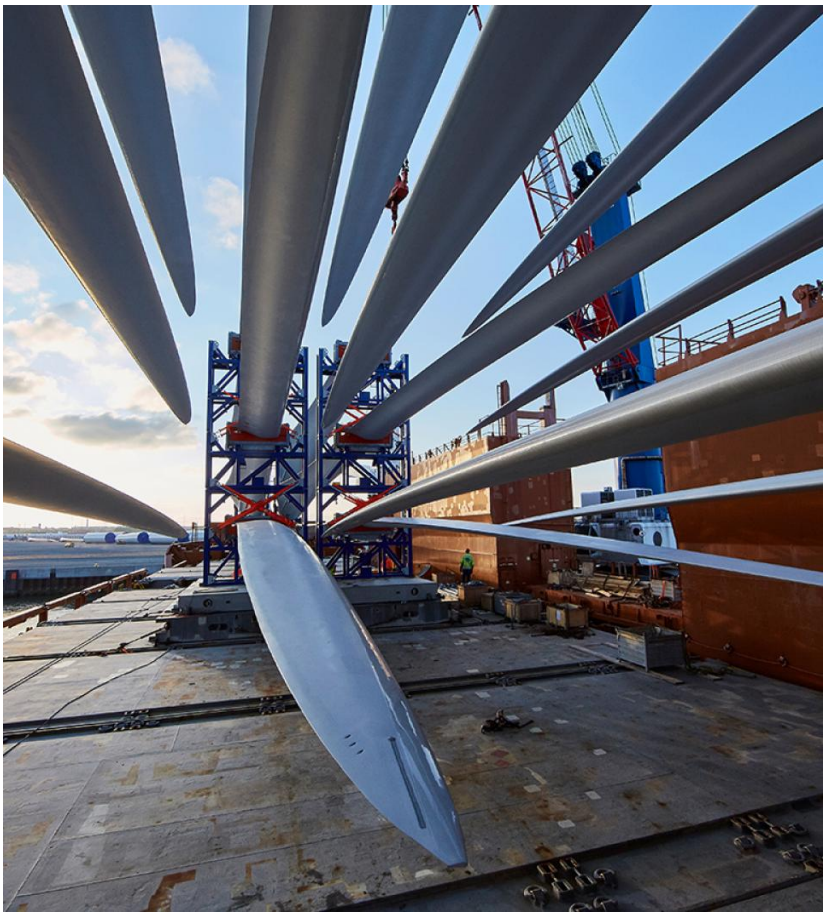


Figure. 13 Low cost thermoplastic material for full wing blade [2]

Image Credits: LM Wind Power

The material used is a low cost thermoplastic skin reinforced by a 3D printed skeleton. This project will open windows in 3D printed wing blades with properties like high fatigue strength, increased rotor diameter, lightweight structures and low maintenance cost [12].

# Conclusions

In this project, we surveyed the physics of the wake models and their limitations. Previous studies indicate that the wake models show good agreement with experimental data provided that the model parameters are tuned according to the atmospheric conditions (Jennifer Annoni et al.,2018) [3].

We have seen that the models like Gaussian consider the changes in atmospheric quantities like wind shear, veer and turbulence intensities. Therefore these wake models can be used in optimization tools(like FLORIS) to perform real time optimization with varying wind conditions. Also, FLORIS can be used to design farm layouts by considering wake losses.

Spatial wind variation for individual turbines was performed via FLORIS which indicated 6.8% power gain for heterogeneous flows over homogeneous flows. Further, FLORIS offered flexibility to simulate various wind farm inputs to evaluate power outputs in consideration with atmospheric conditions. The yaw induced fatigue loads were observed to be reduced for the turbine parts, except the non rotating parts.

Lastly, yaw steering has the potential to improve on power outputs as well as optimizing wind farms, turbines and flow parameters. As well as validating the FLORIS simulation results with LES and experimental LIDAR results.

# References

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[11] Kragh K, Hansen M. Load alleviation of wind turbines by yaw misalignment, Wind Energy. http://dx.doi.org/10.1002/we.1612.

[12] **Tipping Point: 3D-Printed Blade Parts Can Help Take Wind Power To The Next Level | GE News**

# Appendix

**FLORIS Documentation links:**

NREL FLORIS: FLORIS: FLOw Redirection and Induction in Steady State | Wind Research | NREL

Documentation: https://floris.readthedocs.io/en/main/index.html

FLORIS Github link: NREL/floris: A controls-oriented engineering wake model. Documentation at (github.com)