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Executive Summary of the Thesis

Wake Modeling for Downstream Wind Turbine Fatigue Load Estimation

Laurea Magistrale in Energy Engineering - Ingegneria Energetica

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1. Introduction

In recent years great interest was shown towards improving wind turbine technology as its role in the energy transition becomes more and more clear. Amongst the problems yet to solve for this technology, its deployment in wind farm still suffers from the interaction that single wind turbines have on each other through their wakes. Wind Farm control or Active Wake control has as its goal the reduction of negative effects associated with wake interaction such as loss in power generation or more intense aerodynamic loads. To do this two strategies are frequently employed: wake steering and axial induction factor control. The first one works by yawing the upstream turbine with respect to the main wind direction; from the conservation of momentum the wake will then change direction and, ideally, will not impinge completely on the downstream one.

The second one reduces the axial induction factor of the upstream turbine by either pitching the blade or modifying the tip speed ratio, such that the wake will then be more energetic. This technique is also referred to as derating since by modifying the axial induction factor, the turbine works below the optimal power.

While the potential for power production has been already demonstrated [1], the wake control impact on the fatigue loads of the downstream turbine has not yet been estimated. The aim of this thesis is to bridge this gap with a look up table (LUT) approach that tries to minimize the computational burden that is inevitably needed when considering fatigue loads.

2. Wake modeling

For this work a simple wind farm consisting of two DTU 10 MW turbines [2] is considered. The two wind turbines are separated by a distance of 5 rotor diameters (D) and only the upstream turbine is actively controlled through yaw steering and derating. Furthermore to consider the effects of different wind directions, the wind farm's behaviour is analyzed for 5 lateral offsets for the downstream turbine, ranging from -0.5D to 0.5D.

The wake of a wind turbine is made up of two fundamental features: a reduced wind speed and a increased turbulence. Other effects are also present but not modelled in this study. The first property will be referred to as wake deficit and it is modelled, through the use of and engineering wind farm model implemented in the open source code FLORIS, as a Gaussian with peak A, standard deviation σ and coordinates of the wake center (y_c, z_c). In table 1 the models employed by FLORIS for this study are reported.

Submodel	Name
Deficit	Gauss
Deflection	Gauss
Turbulence	Crespo & Hernandez
Combination	Sum of Squares Freestream Superposition

Table 1: Wake models employed in FLORIS

The increased turbulence aspect is modelled through the added turbulence intensity approach, which involves correlations that are generally functions of the thrust coefficient, the downstream distance and the ambient turbulence intensity, to calculate the additional turbulence intensity generated by wake effects. In particular for this study the Quarton-Ainslie [3] correlation is used:

$$I_{add} = 4.8 C_T^{0.7} I_0^{0.68} (\frac{x}{x_N})^{-0.57}$$

where I_0 is the ambient turbulence intensity and x_N is the estimated length of the near wake using the definition of Vermeulen [4]. The turbulence intensity in the wake is then computed as:

$$I_w = \sqrt{I_0^2 + I_{add}^2}$$

Since the downstream distance is fixed and the ambient turbulence is taken as a function of the mean wind speed at hub for the wind turbine class 1A, the wake turbulence intensity depends on both the mean wind speed and the thrust coefficient. The latter, in theory, is influenced by the wind speed as well as the yaw misalignment angle and the derating degree. To simplify the problem, the influence of the upstream turbine control is removed and to obtain at conservative model C_T is calculated for the uncontrolled condition which has the highest possible value for the specific wind speed. Because of this approximations the wake turbulence is considered a function of only the mean wind speed. The parameters of the gaussian wake deficit together with the wake turbulence intensity are then combined to generate the inflow that the aeroelastic software Cp-Lambda receives as input. More specifically the wind is divided into two regions: one characterized by the steady state wake deficit from FLORIS and the wake turbulence and a second one that represents the freestream condition. For each region a wind time series of 10 minutes is generated by TurbSim using the respective turbulence intensity but same mean wind speed and generating seed. On the more turbulent time series the gaussian wake deficit is superimposed to model the effect of the reduced wind speed. The two time series are then merged on a 11x11 points grid and each point is associated with the respective time series depending on if it is inside or outside of the wake. The distinction between the two regions is based on a double criteria: a point is consider in the wake if either its wake deficit is greater than 0.2 m/s or if its distance from the wake center is smaller than 1.48σ. The reason for the first condition is because wake deficit smaller than 0.2 m/s are considered not interesting. The second one is there because 1.48σ is the distance at which the gaussian function assumes a third of its peak value. The choice of this particular distance stems from the intention of obtaining wake widths comparable to the ones seen in literature, such as [5], while also maintaining a compromise that could be conservative but not excessively so.

3. Methodology

The wind farm behavious was analyzed for the following combinations of environmental and operating conditions:

- V_m = [4 5 7 9 11 13 15] m/s
- lateral offset = [-0.5 -0.25 0 0.25 0.5] D
- yaw misalignment = [-25 -15 0 15 25] °
- derating degree = [0 2.5 5 10 15] %

for a total of 875 different inflows seen by downstream turbine. These conditions were run in FLORIS and from it the steady state wake properties were extracted and fitted into the following 2D gaussian function:

$$\delta(y, z) = A \exp^{-(\frac{(y-y_c)^2}{2\sigma^2} + \frac{(z-z_c)^2}{2\sigma^2})}$$

For reference the range in which the four wake parameters vary are here reported:

- A range = [0.16 1.55] m/s
- σ range = [87 149] m
- y_c range = [0 54] m absolute value with respect to the upstream turbine
- z_c range = [128 145] m

Every parameter shows some sort of dependence from V_m but clearly the upstream control seems to have an effect mainly on A (derating) and y_c

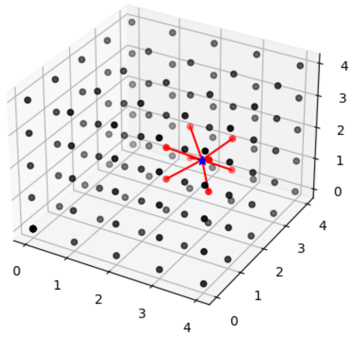

Figure 1: Representation of the binning of the initial case and the selection of a significant case. The blue star stands for the initial case while the 8 red dots surrounding it are the significant cases

(yawing). To select the significant cases to run in the aeroelastic software the domain of the steady state wake properties, excluding z_c, was gridded into an equispaced 5x5x5, obtaining as such for each wake parameter 4 possible bins. Because of the limited variation of z_c its influence on the overall problem was disregarded and for all cases the height of the wake center was considered to be equal to 133.4 m, that is the median of the distribution of the initial 875 cases. For each one of the initial 875 conditions, its steady state wake properties were binned into this grid and as such it is described by a combination of the bins and its mean wind speed. Since there are three wake parameters in actuality means that to fully characterize it by interpolation $2^3 = 8$ cases are needed to be simulated in Cp-Lambda as can be seen in Figure 1.
Because of the fact the gaussian wake behaves predictably by being either wide and shallow or narrow and deep, there exists a strong correlation between A and σ, making most of the significant cases in common between different initial cases. In fact, this procedure cuts down the number of aeroelastic simulations to just 220. Once the significant cases were identified and the inflows generated, the simulations were run. Through Cp-Lambda, 4 loads were chosen to serve as key performance indicators: blade root flapwise and edgewise bending moments and tower base side-to-side (SS) and fore-aft (FA) bending moments. The history of the loads were thus extracted and the DELs computed as by:

$$DEL = (\frac{\sum_i^n (n_i L_i^m)}{T f_{eq}})^{1/m}$$

where n_i is the number of cycles for the ith range, L_i is the load range for the ith range, m is the exponent of the SN curve and f_{eq} is, according to the Standards, the equivalent frequency corresponding to 10M cycles in 20years ($\frac{1 \cdot 10^7}{20 \cdot 365 \cdot 24 \cdot 60 \cdot 60}$ Hz) and T is the simulation time (in seconds). After obtaining the DELs for all of the 220 significant cases the LUT was finally populated.

4. Results

By interpolating linearly over the LUT DEL trends with respect to V_m, lateral offset, yaw angle misalignment and derating degree can be obtained. It must be noted that each of the four loads considered has a unique trend and therefore they are treated separately. For all of them though, no control condition is found to be able to reduce DELs to the point of no wake effects at all; furthermore the greatest variations, in percent terms, are found at mid wind speeds. When considering relative DEL quantities such as the percent increase, the reference case with respect to which they are calculated is the uncontrolled condition so with both yaw angle and derating set to zero.

4.1. Flapwise DEL trends

For all conditions considered the flapwise DEL varies in the range [-8, 4] % indicating an overall small impact when it comes to wake control. When taking into account the reference conditions for each lateral offset the biggest increase compared to ambient condition is at V_m=11 m/s and it is by 19%.
In Figure 2 the effects of derating and steering can be observed. Notably the biggest influence is the lateral position of the wake, for the condition yaw=-25° derating=0% the wake is steered enough for the turbine to experience a decrease in turbulence intensity (Figure 3). By how it was modelled, derating has instead usually a marginal effect and at times even a negative one. This is hypothesized to be due to the fact that its only effect is increasing the mean wind speed seen by the rotor.

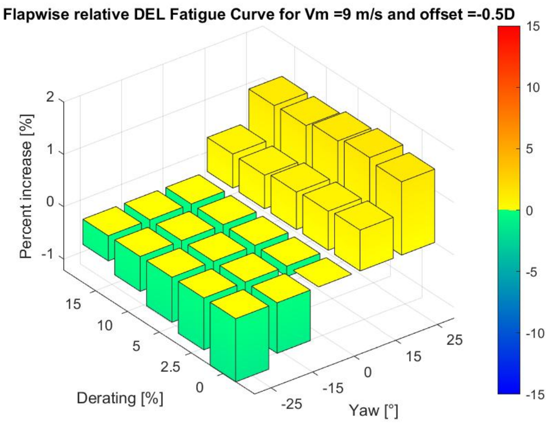

Figure 2: Flapwise DEL trends for V_m=9 m/s and offset=-0.5D

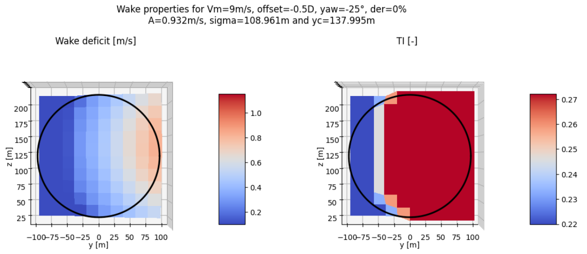

Figure 3: Wake properties and turbulence profile over the rotor disk for V_m=9 m/s, offset=-0.5D, yaw=-25° and derating=0%

4.2. Edgewise DEL trends

For the edgewise loads DELs never vary significantly compared to the ambient condition as it could have been expected, except at V_m=11 m/s where considerable variations take place (Figure 4). This was later attributed to unfortunate initial conditions that give rise to problems for the regulation of the turbine in the first seconds of the simulation. For all other cases, DELs' percent increase range between -0.4% and 0.8 % and as such wake control seem to have little effect on them.

4.3. Side-to-side DEL trends

The SS DEL is by far the load most influenced by wake control, reaching variations in the range [-30, 40] % compared to the respective reference cases and almost doubling the DEL of the ambient case with no wake effects. In Figure 5 the strong variations with respect to the lateral position of the wake can be observed.

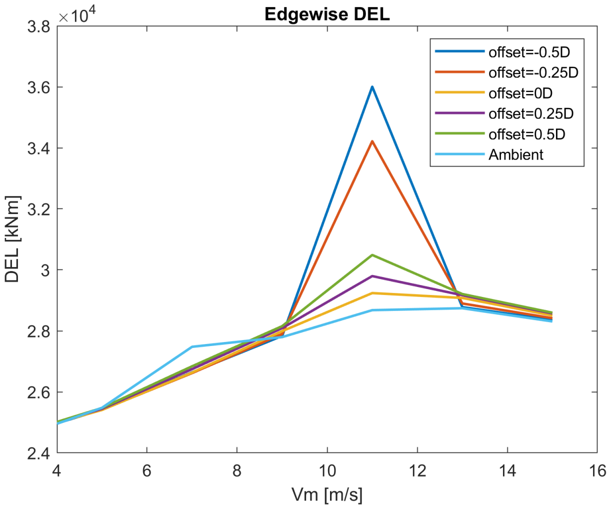

Figure 4: Edgewise DEL curve for the uncontrolled cases as a function of Vm and lateral offset

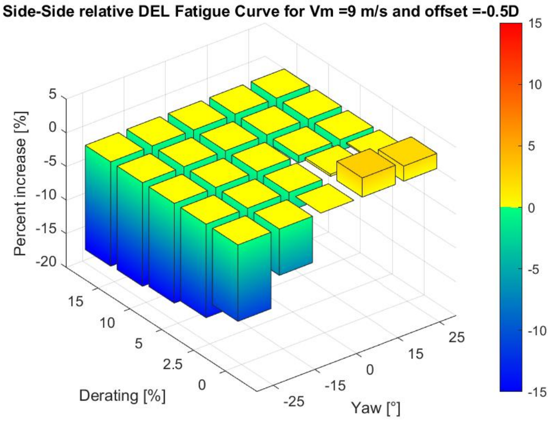

Figure 5: SS DEL trends for V_m=9 m/s and offset=-0.5D

4.4. Fore-Aft DEL trends

Lastly for the fore-aft DELs, percent variations are limited in the range [-6, 6] % and show an overall trend similar to the flapwise ones but with a more skewed tendency to reach DELs decrease compared to the reference condition. This is evident by taking again the V_m=9 m/s and offset=-0.5D as an example (Figure 6).

4.5. Constraint curves

If all four loads' information were to be condensed into a single curve that could show for each lateral offset, in which conditions the turbine always experience a decrease in fatigue loads, the result would be no acceptable combination of yaw-derating at all. This was pre-

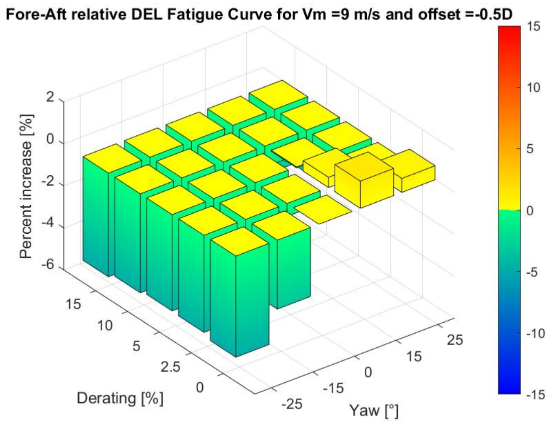

Figure 6: FA DEL trends for V_m=9 m/s and offset=-0.5D

dictable, considering that sometimes completely opposite trends are found amongst the four loads. However if some tolerance for the increase in DELs is introduced and if the SS DELs are not considered since they are not the design loads for the tower, some leeway is obtained for the wake control. In particular to achieve complete freedom of control for the range studied in this work, it would be necessary a tolerance of 5% on increased DELs and the exclusion of the problematic V_m=11 m/s due to the effects it has on the edgewise DELs.

5. Conclusions

Through the method here proposed the impact of upstream wake control on the DELs of the downstream turbine was evaluated. Overall, except for SS DELs and some irregularities for the edgewise DEL, the upstream control manages to vary the fatigue loads on the downstream turbine only slightly. The main factors affecting the DEL variations are, as expected, the increased TI in the wake and the lateral position of the wake deficit which shows asymmetric effects with respect to the hub. Furthermore DELs always sensibly increase compared to the upstream conditions, especially if tower base loads are considered. This last insight suggests that the method should be improved before obtaining reliable results, since, as it is, it is too conservative.

5.1. Future developments

The next step for this study should be certainly to modify the existing wake model with a particular attention to the correlation employed for wake added turbulence as well as a multi region wake in order to capture the peculiarities of its profile. Derating effect on the wake added turbulence should also be considered more explicitly to confidently assess its impact on wake control. Lastly to reduce the uncertainty related to stochastic effects, multiple seeds should be employed for the generation of the wind inflows so that the real deterministic effects could stand out.

References

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