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# Wake steering strategies for combined power increase and fatigue damage mitigation: an LES study

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**Abstract.**
The impact of wake steering control strategy on power production and loads for a cluster of two wind turbines is analysed in this work. The power and loads data base are generated by means of high resolution simulations using an ALM-LES model along with an aeroelastic code for multibody analysis, while the optimal yaw misalignment values are obtained, for different wind directions and performance requirements, using a weighted cost function that accounts for both power production and fatigue damage on main wind turbine components. The sensitivity of the results regarding the inflow conditions, in terms of turbulence intensity, is also analysed. The overall results show that when accounting for both power production and fatigue damage, greater values of optimal yaw misalignment are obtained. This indicates that standard yaw misalignment strategies that accounts only for power production reduce at the same time the loading damage on the wind turbine, compared to greedy configuration.

## 1. Introduction

It is a known fact that wind farm power production and lifetime are strongly affected by the wakes shed by the wind turbines within the wind farm [1]. To improve the wind farms performance – mainly increase their energy production but also extending their lifetime by mitigating the fatigue damage induced by the turbulent and non-homogeneous wake flow – the need of wind farm control strategies that enhance the overall wind farm energy production while reducing the fatigue damage on wind turbines has been advocated. It is expected that such control strategies will indeed contribute in cutting down the levelized cost of the energy produced by wind farms [2].

In this regard, recent works [2, 3] have analyzed how different wind farm control strategies affect both power and fatigue damage of wind turbines, and proposed different methods to assess their impacts. Among the strategies that has been proposed so far, wake steering by misaligning the upstream wind turbines proved to be quite effective, specially when it comes to increase the overall wind farm power production in situations where incident wind direction induces machine-wake interactions [4].

At first, [5] showed that rotating the rotor out of the wind, while maintaining power production at above rated regime, could be an effective method to mitigate the impact of vertical wind shear in turbine fatigue. More recently, the performance of a group of two 5 MW wind turbines was analysed in [6], where the authors studied the impact of a yaw misalignment control strategy that aimed at maximizing the wind farm power output on the Damage Equivalent Loads (DELs) of the upstream wind turbine. The wind farm operation at different wind directions and turbines spacing was modelled using the steady wind farm model FLORIS [7], while the loads data base was generated using the aeroelastic code FAST [8]. The authors concluded that the DEL on the main components of the upstream wind turbine are increased by a small amount in comparison with greedy control strategy, since they expect that the yaw misalignment control strategy will be applied only for a limited fraction of the wind farm life-time. On the other hand, the study in [9] simulated a two 2.3 MW wind turbine plant operating at above wind speed conditions, and the work aimed to assess the DELs experienced by the yaw misaligned downstream wind turbine once partially impinged by the wake shed by the upstream machine. The implemented strategy consisted in finding the optimal yaw misalignment that minimized the blade flap-wise bending DEL, without affecting the power production.

In [3] optimal yaw settings in a wind farm of nine wind turbines arranged in three equal rows is analysed. The optimization strategy consists in minimizing a weighted cost function that accounts for both power production increase and fatigue loads reduction. The wind flow was modelled with FLORIS, which was coupled with a code that implements the Blade Element Momentum (BEM) equations to compute power and loads on wind turbine blades, while the blade flap-wise bending DEL was estimated by computing the variation of the bending moment during one complete rotation. The authors found that yaw misalignment strategy could lead to an increase in power production as well as a reduction of the fatigue damage in situations where partial wake overlap occurs. Similar results were obtained in [10], showing that yaw misalignment control strategy can extend the turbine lifetime of up to 1.5% while increasing the wind farm power production. The analysis was performed running simulations using the mid-fidelity wake model FarmFlow [11] along with a loads data base, previously generated with an aeroelastic code. The authors in [12] used a similar approach to simulate the flow in the wind farm and study the impact of wake redirection by yaw misalignment. The wind turbine loads, obtained by performing several aero-elastic simulations with a 4 MW wind turbine model impinged by different bell-shaped wake profiles, were stored in a Look-Up table (LUT) to be used, along with the mid-fidelity wind farm model, for identifying the optimal yaw setting the increase the overall wind farm power production while reducing the wind turbines DELs.

The general objective of this paper is therefore to expand the work conducted so far, concerning the development of wake steering control strategies that aim at both increasing the wind farm power production while reducing the DELs of the wind turbines main components. In this regard, the impact of wake steering strategies on the power production and DELs for a cluster of two wind turbines has been analyzed first. Furthermore, a specific cost function that accounts for both power production and fatigue damage in the main wind turbine components has been defined, and the optimal yaw misalignments of the upstream wind turbine that maximizes such cost function have been computed for different wind directions and performance requirements. To this aim, power and loads data base are generated by means of high resolution Large Eddy Simulations (LES) coupled with an Actuator Line Model (ALM) along with an aeroelastic code. In addition, this work is intended to analyze the sensitivity of the results regarding the inflow conditions, in terms of turbulence intensity.

## 2. Methodology

For this study, a group of two wind turbines, longitudinally spaced 6D and located on a flat terrain, has been considered. The wind turbine model is the onshore IEA task 37 Reference Wind Turbine described in [13]. This model has a hub height of 110 $m$ and a rotor diameter of 130 $m$, while its rated electrical power and rotor speed are equal to 3.37 $MW$ and 11.75 $RPM$, respectively. These rated values are reached at a wind speed of 9.8 $m/s$.

The wind fields were modelled through LES simulations using open source code caffa3d [14,15] and considering different wind directions $\Phi$ and turbulence intensities. Precursor simulations were performed to simulate a neutral atmospheric boundary layer that impinges the upstream wind turbine. Meanwhile, the simulation of the waked flow that impacts on the downstream turbine was performed using an implementation of the ALM [16] for the upstream wind turbine. For more details on this implementation and its validation, please see [17]. The dimensions of the computational domain are 4 $km$ x 2.25 $km$ x 1 $km$ in the streamwise, spanwise and vertical directions, respectively. The upstream wind turbine was placed four diameters far from the inlet boundary.

Two cases, named **I** and **II** and characterized by different turbulence intensities but similar below-rated wind speed, were simulated. Precursor simulations were therefore performed by setting a roughness length equal to 5 $cm$ and 80 $cm$, for cases **I** and **II** respectively. A similar approach for simulating neutral atmospheric boundary layers with different turbulence intensities can be found in [18]. In order to get an uniform wind speed along the span-wise direction, shifted periodic conditions in the inlet and outlet boundaries were applied following the approach proposed by [19]. The scale-dependent dynamic subgrid-scale model proposed in [20] was used in all the simulations. Table 1 summarizes, for both cases, the main flow characteristics in terms of average wind speed $V_\infty$, turbulence intensity $TI$ and exponent $\alpha$ of the power law profile, commonly adopted for describing the vertical wind profile.

**Table 1.** Description of the wind conditions considered for this study. The values indicates the average along the span-wise direction.

| | **Case I** | **Case II** |
|---|---|---|
| $V_\infty$ [m/s] | 7.9 | 7.7 |
| $TI$ [%] | 8.5 | 13.5 |
| $\alpha$ [-] | 0.07 | 0.15 |

The flow fields simulated with LES were used as input to the aeroelastic code Cp-Lambda [21], which was run in a separate simulation to generate a data base of thirty minutes time series of power and loads for both wind turbines. The fatigue damage is quantified in terms of Damage Equivalent Load (DEL) computed at the blades root, the low-speed shaft and the tower base. A Wholer exponent of 10 was used for DEL computation at the blades, while a value of 4 was used to compute the DELs at both shaft and tower. Both the average power and the DELs were normalized using the average power and DELs of the aligned upstream wind turbine.

With the available data base, optimal yaw misalignments $\gamma$ of the upstream wind turbine that target the overall cluster power increase and fatigue reduction were computed by optimizing the cost function

$$f_c(\Phi, w) = \sum_{i=1}^{n_T} \left[ w\overline{P}_i\left(\Phi,\gamma\right) - (1-w)\overline{\mathrm{DEL}}_i\left(\Phi,\gamma\right) \right], \tag{1}$$

where $\overline{P_i}$ and $\overline{\mathrm{DEL}}_i$ are the normalized power and normalized DEL of one of the three component of the $i$-th wind turbine, respectively, while $w$ is a weighting factor. By maximizing, for each inflow direction $\Phi$, the cost function given by Eq. 1, optimal values of yaw misalignment that either induce the highest power production ($w = 1$), the lowest fatigue damage on a specific wind turbine component ($w = 0$) or the maximum of the weighted sum of these two terms, were therefore obtained.

## 3. Results

In this section, the results regarding normalized power and DELs of the two wind turbines are shown for different wind directions and yaw misalignment of the upstream machine. The blade root DELs were obtained by projecting the blade root flap-wise and edge-wise bending moments on the direction associated to the maximum DEL. This methodology is considered to be more precise, when assessing the blade damage, than analysing the flap-wise and edge-wise bending moments separately. In a similar manner, the DELs at the low-speed shaft were obtained projecting the yawing and nodding bending moments along the direction associated to the maximum DEL, while fore-aft and side-side bending moments were considered for the computation of maximum DEL at tower base. The optimal yaw misalignment obtained for different wind directions and values of the weighting factor is also presented in two subsections regarding cases **I** and **II**, which correspond to low TI (8.5%) and high TI (13.5%) respectively.

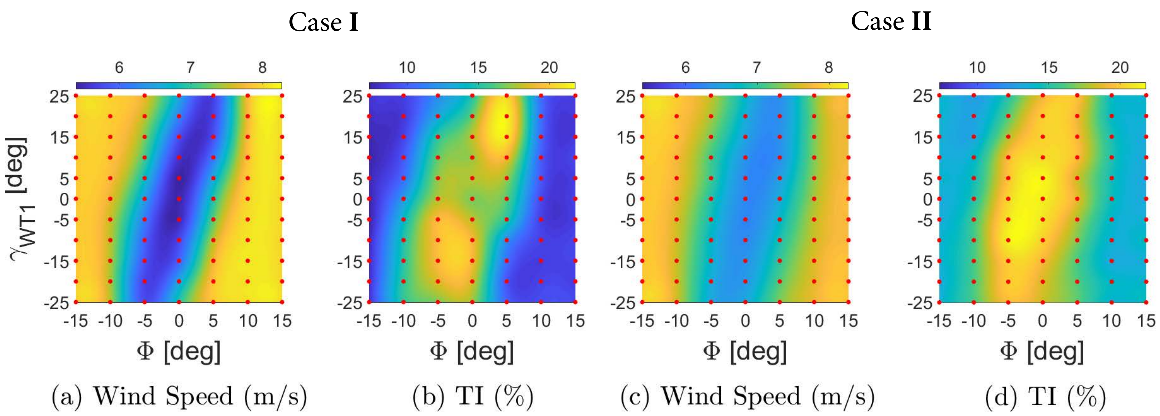


**Figure 1.** Left: Mean wind speed (a) and turbulence intensity (b) measured by the downstream turbine at hub height in case **I**, as functions of $\Phi$ and $\gamma$. Right: Mean wind speed (c) and turbulence intensity (d) measured by the downstream turbine at hub height in case **II**, as functions of $\Phi$ and $\gamma$.

**Table 2.** Power and DELs values used for normalization in each case of study.

| | **Case I** | **Case II** |
|---|---|---|
| Power [MW] | 2.0 | 1.8 |
| Blade Root DEL [MNm] | 5.66 | 5.80 |
| Low-Speed shaft DEL [MNm] | 4.78 | 4.69 |
| Tower base DEL [MNm] | 5.45 | 8.26 |

Figure 1 shows, for cases **I** and **II**, the effects of yaw misaligning the upstream wind turbine on the inflow characteristics, in terms of mean wind speed and turbulence intensity, measured by the second wind turbine at hub height. It can be observed that the wind speed experienced by the downstream turbine is reduced while the turbulence intensity increases, due to the presence of the wake. It is also interesting to observe that the turbulence intensity experienced by the downstream wind turbine in case **I** can be up to three times higher than the turbulence intensity in the free flow experienced by the upstream wind turbine. Meanwhile in case **II**, the turbulence intensity measured by the downstream wind turbine is never greater than 1.7 times the turbulence intensity experienced by the upstream turbine.

Table 2 shows the average power and DELs of the aligned upstream wind turbine, used for normalization in cases **I** and **II**. The values reported in this table show a very low sensitivity of the DELs computed at the blade root and the low-speed shaft with respect to the turbulence intensity. It could be explained by the fact that DELs are computed on the direction associated to the maximum DEL, as explained before in this section, and therefore the rotor speed has a sensible impact on these computed values. As a consequence of this, it looks like the effect that a greater TI in case **II** might have in DELs at blade and low-speed shaft, is being compensated by the fact that the power produced, and thus the rotor speed, by the upstream turbine in case **II** is lower than in case **I**.

### *3.1. Case I: low TI*

Figure 2 shows normalized power and DELs for the upstream and downstream wind turbine, respectively, as function of wind direction and upstream machine yaw misalignment, where a positive yaw angle corresponds to a counter-clockwise rotation, viewed from the top, of the nacelle. Moreover, the wind direction $\Phi$ is null when the imaginary line that passes through the two rotor hubs is aligned with wind vector, and positive for a counter clockwise rotation of the wind vector, when viewed from the top.

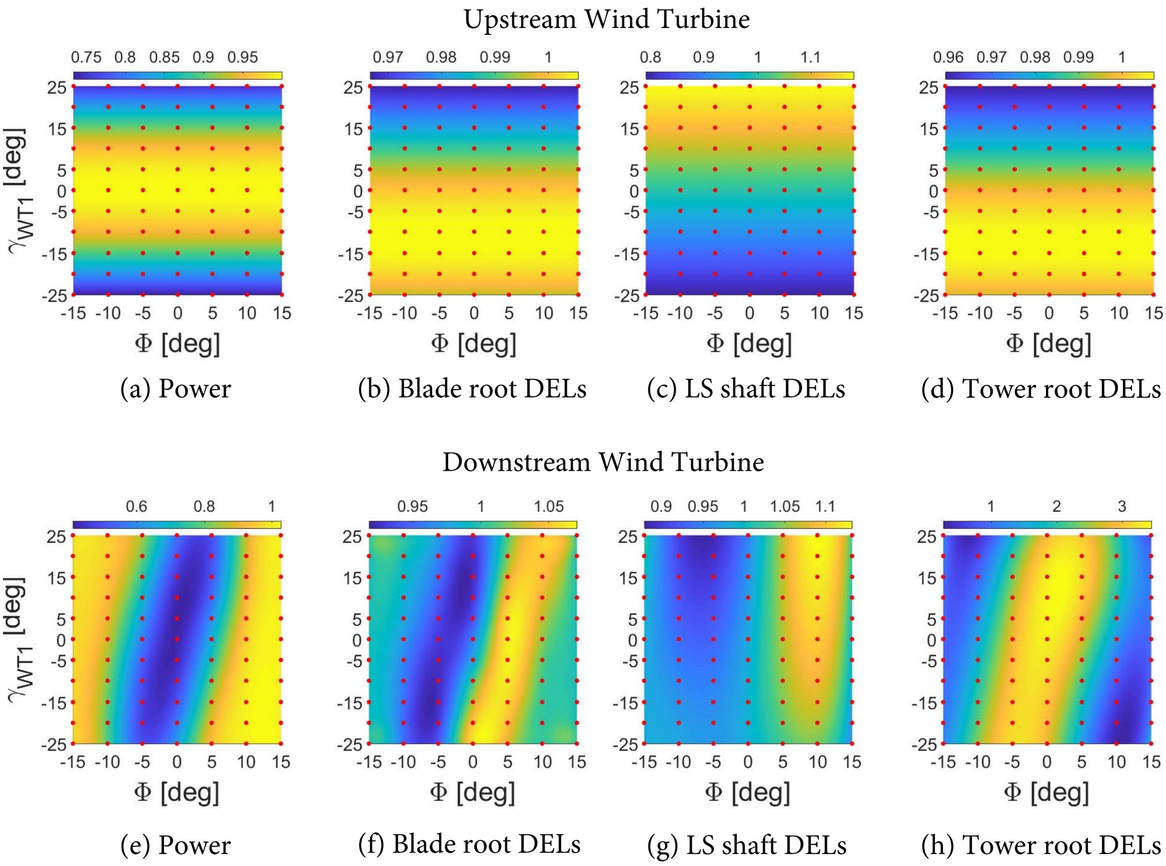


**Figure 2.** Above: upstream wind turbine normalized power (a) and DELs computed at:(b) blade root, (c) low-speed shaft and (d) tower base as function of $\Phi$ and $\gamma$. Below: downstream wind turbine normalized power (e) and DELs computed at:(f) blade root, (g) low-speed shaft and (h) tower base as function of $\Phi$ and $\gamma$. The results were obtained for below rated wind speed and low turbulent inflow (case I).

Blade root and tower base DELs behaviour shown in Figure 2 for the upstream wind turbine are in accordance with results obtained in [6]: the DELs are indeed reduced by positively misaligning the turbine. An opposite trend is observed in this study for the low-speed shaft DEL, which is sensibly reduced for negative values of the yaw misalignment.

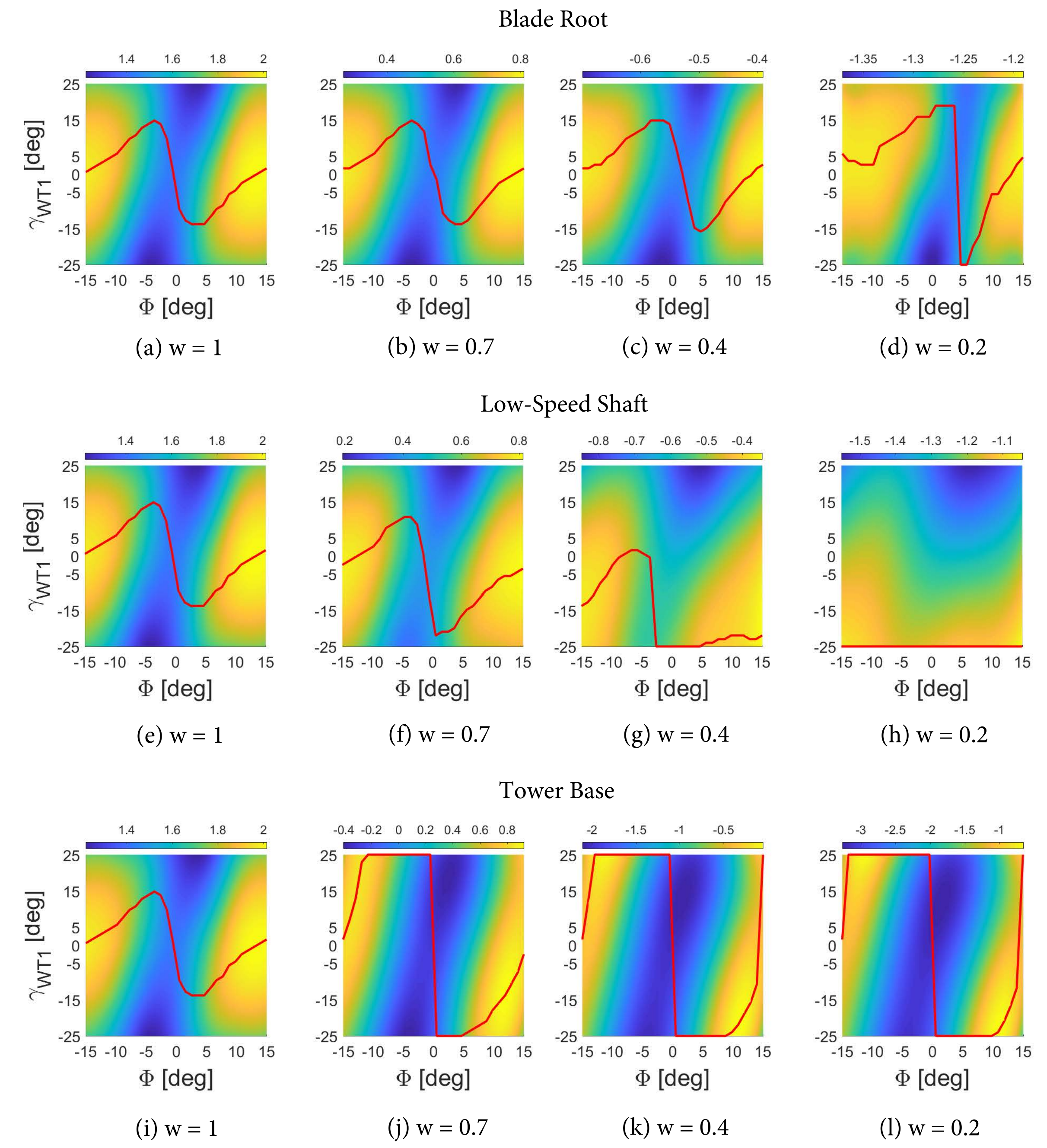


**Figure 3.** Cost functions with respect to $\Phi$ and $\gamma$ for low TI (case I), different values of the weighting factor and turbine components DELs. The red line depicts the corresponding optimal yaw misalignment.

Figure 2-e shows a reduction of the power produced by the downstream turbine due to the

waked flow, with a minimum value of the normalized power equal to 0.4 for null $\Phi$ and $\gamma$. The trend of the blade root DEL well agrees with the one of the produced power, i.e. the DELs are low when the produced power is close to its observed minimum. The reason can be traced back to the fact that the considered DEL is mainly governed by the edgewise bending moment fluctuations, which in turn are strongly correlated to the rotational speed and, therefore, to the produced power. The distribution of the tower root DELs (Fig. 2-h), instead, highlights that high DELs are observed when the produced power is low (Fig. 2-e), which implies that the tower damage is proportional to the wake losses (Fig. 2-a), and to the turbulence intensity in the wake (Fig. 1-b).

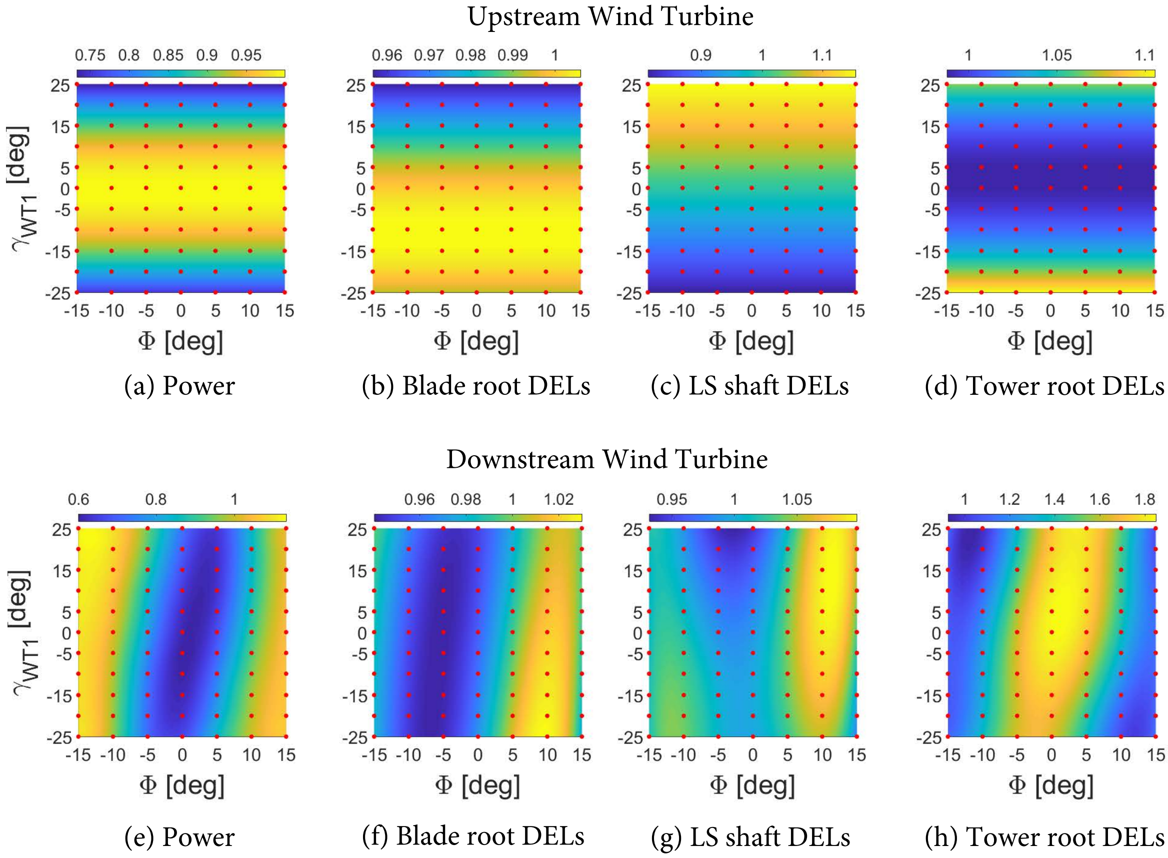


**Figure 4.** Above: upstream wind turbine normalized power (a) and DELs computed at:(b) blade root, (c) low-speed shaft and (d) tower base as function of $\Phi$ and $\gamma$. Below: downstream wind turbine normalized power (e) and DELs computed at:(f) blade root, (g) low-speed shaft and (h) tower base as function of $\Phi$ and $\gamma$. The results were obtained for below rated wind speed and high turbulent inflow (case II).

Figure 3 shows four distributions of the cost function expressed by Eq. 1 which were obtained for four different values of the weighting factor $w$, and considering both power and DELs associated to different wind turbine components. The reader should note that different colormaps were adopted for each value of the weighting factor. The depicted red lines, which show the yaw misalignments that maximize the corresponding cost function for each wind direction, indicate that greater yaw misalignment angles are required when the wake steering strategy accounts not only for power production, but also for the alleviation of blade root or tower root DELs. When damage reduction of the low-speed shaft DEL is majorly accounted in the cost function ($w = 0.2$), an optimal yaw value of $-25°$ is obtained for the entire range of wind direction. This can be explained by the fact that with $w = 0.2$ a strong cost function reduction can be obtained if the DEL of the upstream turbine is reduced by adopting negative values of yaw misalignment, as shown in Figure 2-c.

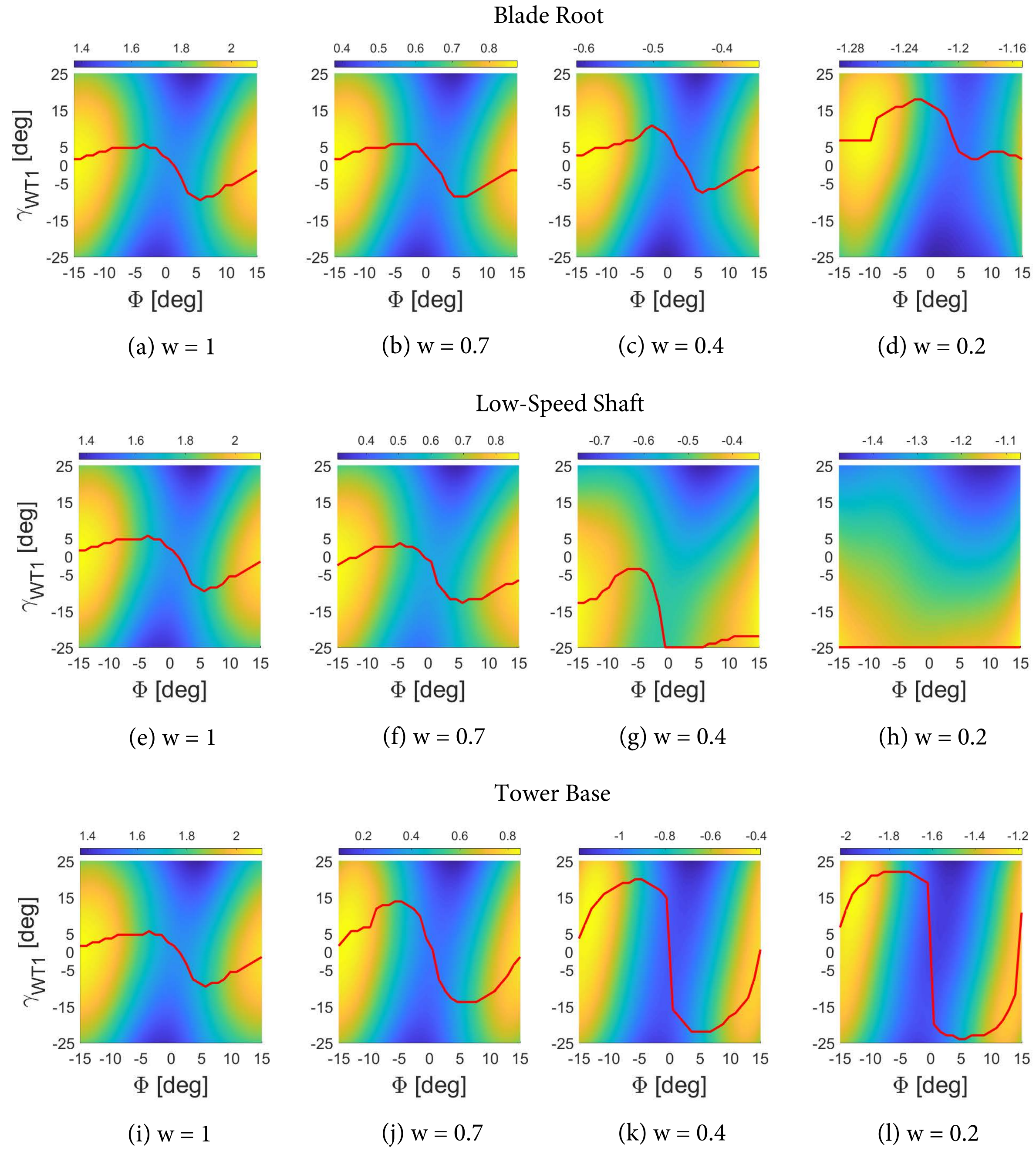


**Figure 5.** Cost function with respect to $\Phi$ and $\gamma$ for high TI (case I), different values of the weighting factor and turbine components DELs. The red line depicts the corresponding optimal yaw misalignment.

### 3.2. Case II: high TI
Figure 4 shows normalized power and DELs for the upstream and downstream wind turbine, respectively, when a highly turbulent flow impinges the turbines.

Figures 4-a to 4-d indicate similar trends than those observed in Figures 2-a to 2-d, except for the case of DEL at the tower root which shows a minimum value when the rotor is aligned with the flow. Figures 4-e to 4-h show similar normalized DEL results than the ones observed in Figures 2-e to 2-h for the downstream turbine. Although, the absolute values of DELs obtained in the simulations are sensitively higher in case II. This was an expected result, due to greater flow turbulence intensity and so wake recovery, which leads to greater power production and rotational speed of the downstream turbine.

Figure 5 shows the yaw misalignment that maximize the corresponding cost function for each wind direction in case II. A similar trend can be observed with respect to case I when the weight factor decreases. However, the results show that lower yaw misalignment should be applied for weight values close to 1. As it can be observed in Figures 2-a (case I) and 4-a (case II), the power produced by the upstream wind turbine is quite reduced when the yaw misalignments are greater than 10 degrees or lower than –10 degrees. For this reason, when the optimization strategy only accounts for maximization of the cluster power, the optimal yaw misalignment is the one that makes the power reduction experienced by the upstream wind turbine the lowest compared to the power increase experienced by the downstream wind turbine, and this is achieved for not that high yaw misalignments.

## 4. Conclusions
Results obtained in this work indicate that greater values of yaw misalignment are required when accounting for both power production and fatigue damage, compared to a strategy in which only power maximization is pursued. This means that standard yaw misalignment strategies that accounts only for power production reduce at the same time the loading damage on the wind turbine, compared to greedy configuration. This is not true only in the case of the low-speed shaft, that increases the damage when only power maximization is pursued for negative values of flow angle.

The upcoming work is intended to follow the same methodology described in this document to analyse the sensitivity of the results regarding different wind speeds and wind turbine structural characteristics.

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