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Reduced Design Load Basis for Ultimate Blade Loads Estimation in Multidisciplinary Design Optimization Frameworks

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Abstract.   The aim is to provide a fast and reliable approach to estimate ultimate blade loads for a multidisciplinary design optimization (MDO) framework. For blade design purposes, the standards require a large amount of computationally expensive simulations, which cannot be efficiently run each cost function evaluation of an MDO process. This work describes a method that allows integrating the calculation of the blade load envelopes inside an MDO loop. Ultimate blade load envelopes are calculated for a baseline design and a design obtained after an iteration of an MDO. These envelopes are computed for a full standard design load basis (DLB) and a deterministic reduced DLB. Ultimate loads extracted from the two DLBs with the two blade designs each are compared and analyzed. Although the reduced DLB supplies ultimate loads of different magnitude, the shape of the estimated envelopes are similar to the one computed using the full DLB. This observation is used to propose a scheme that is computationally cheap, and that can be integrated inside an MDO framework, providing a sufficiently reliable estimation of the blade ultimate loading. The latter aspect is of key importance when design variables implementing passive control methodologies are included in the formulation of the optimization problem. An MDO of a 10 MW wind turbine blade is presented as an applied case study to show the efficacy of the reduced DLB concept.

1. Introduction

One of the key aspects for the design of a wind turbine blade is the estimation of ultimate loads. A reliable evaluation of ultimate loads is an intricate problem due to the stochastic nature of turbulence and the nonlinear dynamic behaviour of the system. To face the complexity of this issue, the standards require a large amount of simulations, which can represent an excessive computational effort. This effort becomes impractical when a turbine is preliminary designed with an MDO. In optimization frameworks, the computation of ultimate loads is of crucial importance when design variables implementing passive control

methodologies are included in the process. These variables can produce substantial variations in the distribution of the loading on a wind turbine blade, requiring constant updates for the ultimate strength constraints. Consequently, there is a need of a scheme able to give a sufficiently accurate and quick estimation of the variation of the ultimate blade load envelopes during an MDO.

The wind turbine MDO frameworks developed in recent years already presented different solutions to this problem. Some of these frameworks assume that the blade load envelopes are *frozen* either at each step of the optimization process [1], either in a nested multi-stage MDO [2]. In general, a full DLB is computed outside the most computationally expensive loop, and the ultimate blade strength constraints remain unchanged throughout that MDO stage. The frozen loads assumption is valid if the load envelopes change slowly with respect to changes in the design variables, and if the optimization problem for a particular design is not exclusively driven by ultimate strength constraints. Another approach to simplify the calculation of ultimate blade loads is to use only a very restricted amount of design load cases (DLCs) [3, 4, 5]. The selection of these DLCs, which should represent the most strength-critical situations for the blade structure, is based on the experience of the designer.

In this paper, a fast method to compute ultimate blade load envelopes sufficiently accurate for an MDO is presented. The proposed scheme has the advantage of being so computationally cheap that can be included in the optimization loop, eventually dropping the frozen loads assumption. It can take into account all the effects that drive standard DLCs without exclusively relying on the designer experience, and without being dependent from the wind turbine design. The key behind the proposed ultimate blade load analysis strategy is the substitution of turbulent load cases with sets of "deterministic" DLCs. The effect of the turbulent inflow is mimicked using custom-made shear zones and extreme operating gusts. Consequently the amount of simulations and the simulation time are drastically decreased. Limitations connected to the substitutions of the turbulent DLCs need careful considerations.

The first section of this paper provides a description of the models used. The DTU 10 MW reference wind turbine (RWT) [6] is chosen as the baseline design for this study. The second section presents in details the methodology of the reduced DLB concept. To test the efficacy of the latter, ultimate blade load envelopes are calculated for the baseline design and a design obtained after a generic MDO. The results section shows that the envelopes computed for a full standard design load basis (DLB) [7] and the reduced DLB for the two designs have similar characteristics that can be exploited following a workflow presented in the methodology section. Positive and negative outcomes behind the use of the reduced DLB approach are discussed. In the last section, a test case implemented in the DTU MDO framework HAWTOPT2 [1] is reported to provide an application for the reduced DLB approach.

2. Models
The nonlinear models used for the estimation of the load envelopes are implemented in the time-domain aero-servo-elastic code HAWC2 [8, 9]. The multi-body formulation used by the structural part of HAWC2 is presented and validated in [10]. The description and the validation of the unsteady BEM method used by the program can be found in [11, 12, 13].

As mentioned in the introduction, the testing of the reduced DLB concept passes through the computation of a typical standard DLB. For this study, the "DTU Design Load Basis for onshore turbines - Revision 00" [7] is selected. The DTU 10 MW RWT [6] coupled with the

Basic DTU Wind Energy Controller [14] are used as the baseline turbine.

The final test case presented in the last section is computed through an optimization process carried by the HawtOpt2 framework [1, 15]. Built on the platform provided by OpenMDAO (Open-source Multidisciplinary Design, Analysis, and Optimization Framework) [16, 17, 18, 19], the tool is used to handle the definition of the optimization problem, workflow, dataflow, and parallelization of simulation cases. OpenMDAO provides an interface to PyOpt [20], a container for several optimization algorithms. In this work, the gradient-based sequential quadratic programming optimizer SNOPT [21] is used.

3. Methodology

The stochastic nature of the turbulence adds complexity to the estimation of the ultimate loads. As briefly mentioned in the introduction, to face the intricate matter of simulating wind turbine loading in turbulent inflow conditions, a standard DLB requires an high amount of simulations (the DTU DLB counts up to 1880 DLCs). The number of simulations depends on the amount turbulence seeds considered, which is usually as large as possible to obtain wind turbine loads with sufficient accuracy. Taking into account such a number of simulations in an MDO can become impractical due to the computational effort and time required to perform each cost function evaluation. Moreover, turbulent DLCs are lengthy simulations (usually the standard simulated time is 10 minutes), which can represent a further obstacle to keep the optimization time reasonable.

Another issue is the fact that the interaction of a changing turbine design with different parts of the same turbulent field during an MDO might compromise the quality of the optimization process [22].

In the light of these problems, the main idea behind the formulation of the reduced DLB for the estimation of ultimate loads in MDO frameworks is to use a "deterministic" set of load cases able to mimic the effects of turbulence on the blade loading. These "deterministic" DLCs are characterized by the presence of a custom-made shear zone or extreme operating gusts. A detailed description is provided in the next part of the section.

The absence of turbulence from the DLB gives the possibility to greatly shorten both the amount of simulations (no turbulence seeds need to be considered) and the simulation time of each DLC selected (without turbulence a simulated time of 10 minutes is no more a requirement). This translates in a consistent advantage with respect to computation time, which is consistently shortened for the aero-servo-elastic code used for the study. The time required to run an HAWC2 simulation of the reduced DLB is suited for efficient MDO.

In the next part of this section, a full description of the reduced DLB is provided, along with an explanation of "deterministic" set of load cases aforementioned. The section concludes with a part dedicated to how this reduced DLB concept can be integrated in an wind turbine blade MDO problem.

3.1. The Reduced DLB

The main characteristic of the reduced DLB is the substitution of turbulent load cases with a set of "determistic" ones. The substitution brings a significant reduction in the amount of the DLCs and simulation time. Moreover, as the presence of stochastic inflow conditions can compromise the results of the MDO process, the ultimate blade load envelopes are computed through simulations that use deterministic changes in the inflow. In this manner, a blade design changing during the MDO will always interact with the same wind field structure,

ensuring a more robust evaluation of the variations in wind turbine loading due to a change in a design variable. At each cost function evaluation, the new design undergoes the same wind loading excitations than its predecessor ensuring, for example, that the optimization process is not depending on the position occupied by the blade in a stochastic inflow field. Two wind flow conditions are used to substitute the turbulent inflow load cases:

- a custom-made shear for production, fault, start-up, and shut-down load cases;
- an extreme operating gust (EOG) for parked and maintenance DLCs.

Figure 1 provides a visual representation of the first deterministic wind field variation used by the reduced DLB. When a blade rotates towards the upward positioning, it passes through a custom-made shear zone, formed by a combination of a linear horizontal shear and a linear vertical shear. At the center of the hub, the wind speed, defined by the coordinate system $< u, v, w >$ that follows the notation in the HAWC2 manual [9, p. 21], is equal to the uniform wind speed selected for the specific DLC ($u_1 = V_{hub}$ and $v_1 = V_{hub}$). Above the hub height, the wind speed increases towards the outer part of the rotor until it reaches the value defined in Equation 1. The rest of the wind inflow is uniform and it has a constant value of V_{hub}.

$$u_2 = V_{hub} + 3\sigma_1; \quad v_2 = V_{hub} + 3\sigma_1 \tag{1}$$

where V_{hub} is the wind speed at hub height selected for a specific DLC, and σ_1 is the representative value of the turbulence standard deviation as defined by the IEC standard [23, p.24-27] and reported in Equations 2 and 3 for normal and extreme turbulence models, respectively.

$$\sigma_1 = I_{ref}(0.75 V_{hub} + b); \quad b = 5.6\,\mathrm{m\,s^{-1}} \tag{2}$$

$$\sigma_1 = c\, I_{ref} \left[0.072 \left(\frac{V_{ave}}{c} + 3\right) \left(\frac{V_{hub}}{c} - 4\right) + 10\right]; \quad c = 2\,\mathrm{m\,s^{-1}}; \quad V_{ave} = 0.2\, V_{ref} \tag{3}$$
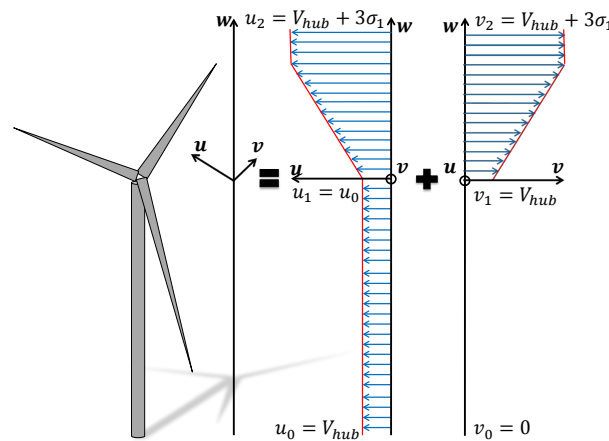

Figure 1: Visual representation of the custom-made shear zone used to mimic ultimate blade loading generated by turbulent inflow. The sheared wind inflow is assembled by the combination of a linear horizontal shear and a linear vertical shear in the upper part of the rotor. Values of the wind speed in the different areas of the shear zone are highlighted in the equations.

where V_{ref} and I_{ref} are the reference wind speed and turbulence intensity, respectively, which depend on the turbine class. Since the DTU 10 MW RWT belongs to the class IA, $V_{ref} = 50\mathrm{m\,s}^{-1}$ and $I_{ref} = 0.16$.

The idea behind the use of the described custom-made shear zone is to apply to each blade a loading with the highest peak at 1P both in the flapwise and the edgewise directions. This type of loading is typical for wind turbines due to shear, tower shadow, and nacelle tilt, and it represents the most important contribution to blade loads in turbulent inflow conditions. The wind profile in the custom-made shear zone (Equations 1, 2, and 3) is selected to take into account the maximum wind speed variations present in the turbulence DLCs.

The second deterministic wind field variation is an EOG, which is implemented in the reduced DLB following the formulation provided by the IEC standard in [23, p. 26].

The effect of turbulence on the loads cannot be exactly replicated, but the maximum and minimum flapwise and edgewise blade loads can be caught with a sufficient accuracy, as shown in the next section. Furthermore, the proposed scheme to mimic turbulent DLCs is based on general observations of typical wind turbine loads, and it can be therefore applied to different wind turbine designs and classes.

A complete summary of all the load cases that constitute the reduced DLB used for the RWT is reported in Appendix A. Only the ultimate DLCs are part of the DLB (label "U" in [7, p. 7]). The partial safety factors used for each DLC are the same used in [7]. The load cases that do not consider turbulence in the DTU DLB are kept unchanged (DLC14, DLC15, DLC23, DLC32, DLC33, and DLC42). Simulated time is not reported because it is not a strict requirement for the reduced DLB, and it can be chosen according to the aero-servo-elastic models used. Controller faults dependent load cases (DLC22) are not considered for the time being, as they were not included as design load cases for the DTU 10 MW RWT. These DLCs are going to be included in a future development of the reduced DLB.

3.2. Intergration of the reduced DLB in an MDO framework

The reduced DLB concept can be integrated in an optimization problem for the design of a wind turbine blade. As shown in details in the next section, the envelopes obtained through the computation of the reduced DLB are similar in shape to the one obtained from a full DLB, but different in magnitude. For this reason, the reduced DLB can be used directly in the MDO as an indicator of the load variations following the scheme depicted in Figure 2. A detailed description of the steps of the integration process are highlighted in the figure's caption.

The optimization problem is supplied with blade load envelopes coming from a full DLB. Then, a correction, based on the load variations caught by the reduced DLB, is applied every cost function evaluation. The deterministic nature of the reduced DLB does not compromise the optimization process, which is quickly provided with new ultimate blade load envelopes at each step. Moreover, the most time-consuming part of the process (the estimation of envelopes with a full DLB) is done outside the optimization loop.

4. Results

The purpose of this section is to show that an ultimate loading variation estimated through a reduced DLB is similar to load variations estimated by a much more computationally expensive DLB. If this assumption is verified, the reduced DLB can be suitable for ultimate
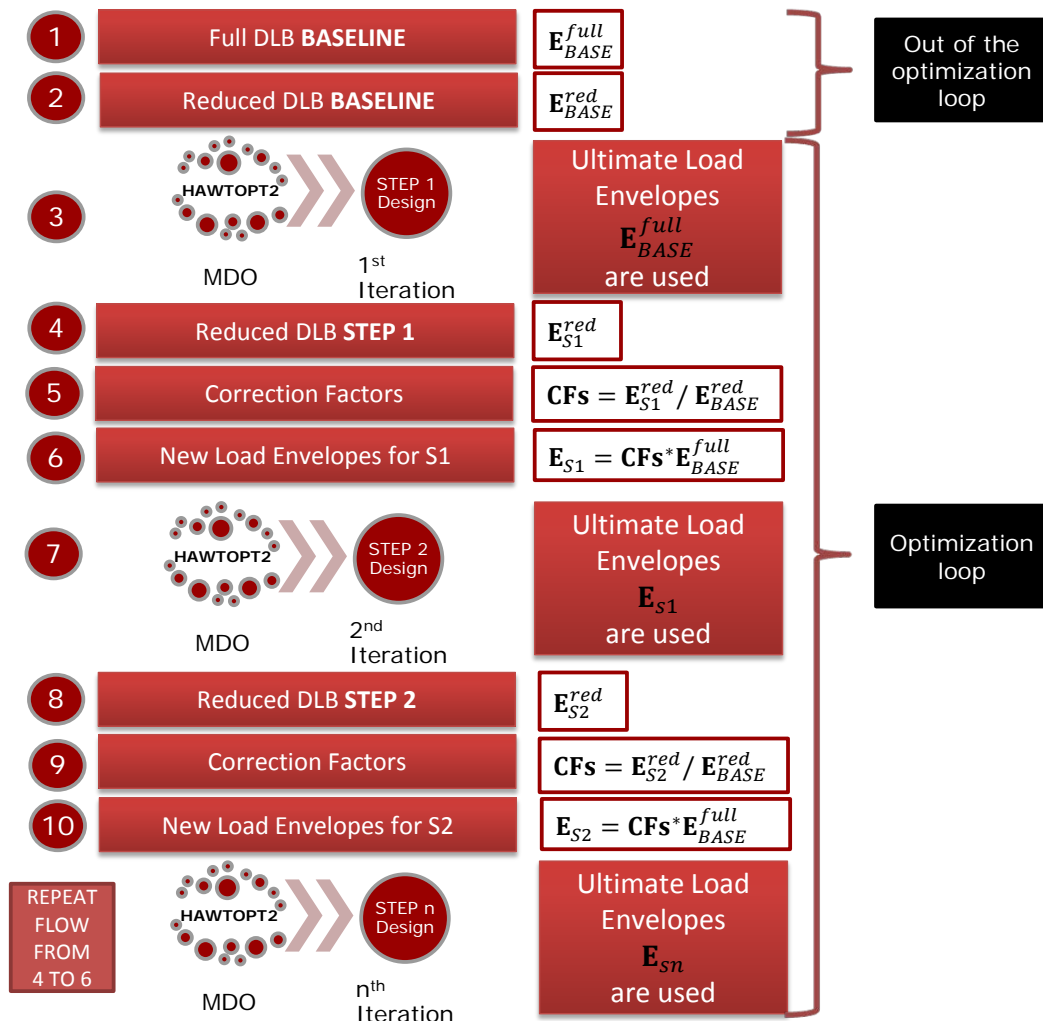
Figure 2: Description of the integration of the reduced DLB concept in an MDO framework. 1 - Out-of-the-optimization-loop estimation of ultimate load envelopes with full DLB for the starting design ($\mathbf{E}_{BASE}^{full}$ is a matrix containing cross sectional forces and moments for each envelope point and each blade section). 2 - Out-of-the-optimization-loop estimation of ultimate load envelopes with reduced DLB for the starting design ($\mathbf{E}_{BASE}^{red}$). 3 - Starting from the baseline design, the MDO is carried until it reaches a new design (Step 1 design). The baseline full DLB ultimate load envelopes ($\mathbf{E}_{BASE}^{full}$) are used. 4 - The load envelopes are estimated with the reduced DLB on the Step 1 design ($\mathbf{E}_{S1}^{red}$). 5 - Correction factors **CFs** are obtained from the baseline reduced envelopes and the step 1 design ones (see equation). 6 - The correction factors are used to calculate the envelopes at the next cost function evaluation ($\mathbf{E}_{S1} = \mathbf{CFs} * \mathbf{E}_{BASE}^{full}$). 7 - The corrected ultimate blade loads are ready to be applied on the next iteration of the optimizer, which will produce a new design (Step 2 Design). 8/10 - Same procedure from point 3 to 5 is applied on Step 2 design.

blade load envelopes estimation in an MDO process, and the scheme described in Figure 2 can be applied.

Figure 3 shows a comparison between ultimate load envelopes (plot on the top left) of the Baseline and of the Step 1 designs extracted using the full and the reduced DLBs. The Step 1 is a blade design resulting from the first cost function evaluation of an MDO, where the design variables include both aeroshape and internal structure of the blade. The load envelopes are calculated at a blade radial station located at approximately 51m. Along with the envelopes, the ultimate loads projected in 4 directions (maximum and minimum flapwise moments, 0° and 180° respectively, maximum and minimum edgewise moments, 90° and -90° respectively) are compared. The bar plot at the bottom of the figure shows the ultimate loading variations in these 4 directions obtained with the full and the reduced DLBs. The latter plot shows how the reduced DLB is able to catch the quality of these variations.

A full overview of the projected ultimate flapwise and edgewise loads in both directions for each section of the blade is shown in Figure 4. The plots compare the variations between maximum and minimum flapwise and edgewise loads calculated using a full standard DLB and the reduced DLB, respectively.

Figure 3: Comparison of ultimate load variations calculated between Baseline and Step 1 design using the full and the reduced DLB. The load envelopes are calculate for a section located at 51m along the blade length. The plot on the top left describes the envelopes, while the plot on the top right describes the ultimate loading projections along 4 directions, namely maximum and minimum flapwise moments, 0° and 180° respectively, maximum and minimum edgewise moments, 90° and -90° respectively (loading directions also plotted on the bottom-left plot). The bar plot shows the variations in ultimate loading in the 4 directions just listed for the full and the reduced DLB.

The variations in percent are estimated as $\mathbf{V}(r) = (\mathbf{E}_{S1}/\mathbf{E}_{BASE} - 1) * 100$, where r is the blade radius.

The reduced DLB approach is able to replicate the trend of the load variations computed using a standard DLB especially in the outer part of the blade. The reduced DLB overestimates the decrease in loading observed for the minimum flapwise direction (second plot of Figure 4). More discrepancies between the loads computed by the two DLBs can be observed in the inner part of the blade in both the edgewise directions. These differences depend on the fact that the ultimate loads in the directions just listed are driven by the DLC 1.3, where an extreme turbulence model is used to evaluate loads in a standard DLB. The reduced DLB can only mimic the effect of turbulence, and it is not able to fully catch the loading driven by an extreme turbulent load case. Specifically, in turbulent inflow conditions, wind speed and direction might vary considerably along the blade span, causing loading variations difficult to replicate with the simplified approach proposed in this work. Nonlinear dynamics of the system and behaviour of the controller add further complexity when it comes to mimic the effects of turbulence.

Despite these problem, the reduced DLB approach catches very well the quality of these variations along all the blade span. The custom-made shear zone is able to replicate well the 1P loading excitation that is the main load contribution for a wind turbine undergoing turbulent DLCs. The extreme operating gusts are enough to catch the wind speed variations
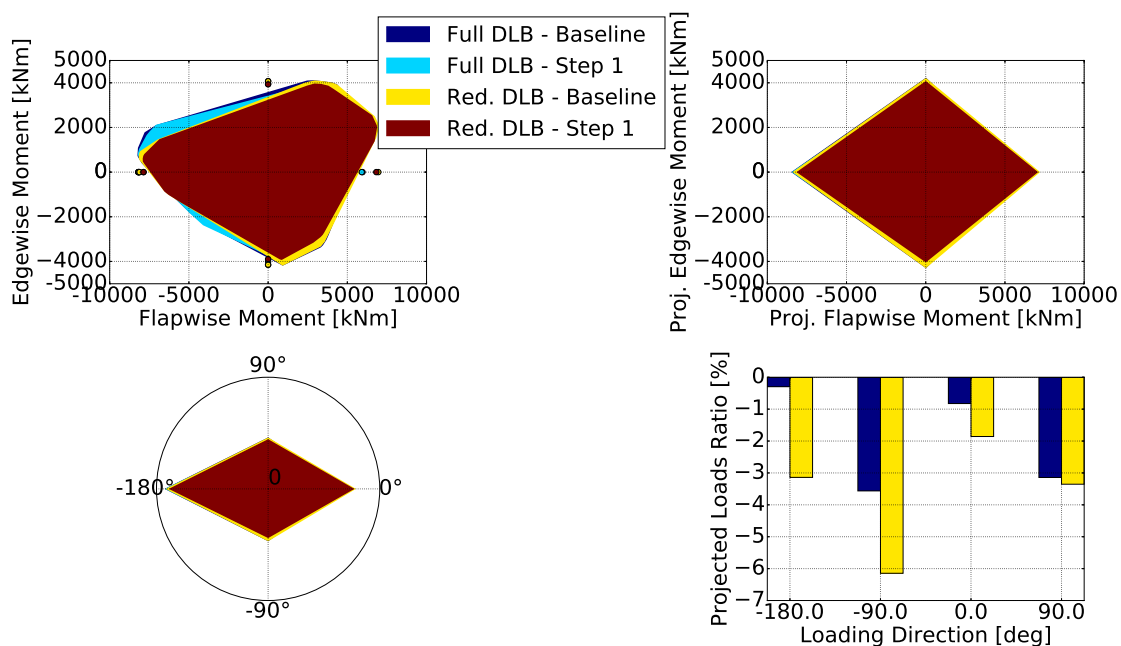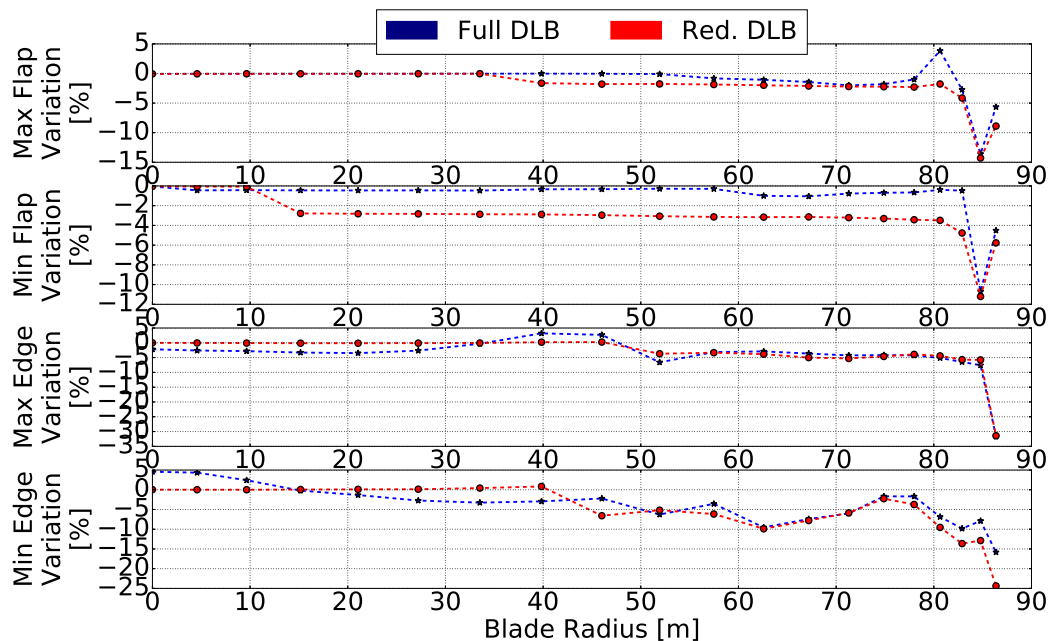

Figure 4: Comparison of ultimate load variations calculated between Baseline and Step 1 design using the full and the reduced DLB. The plots are listed in this order proceeding from top to bottom: maximum pure flapwise load variations along the blade radius; minimum pure flapwise load; maximum pure edgewise and minimum pure edgewise.

in the parked and maintenance load cases.

In the next section, the results from an optimization test case are reported to demonstrate the efficacy of the reduced DLB approach applied in an MDO framework.

5. Application on a Case Study

The reduced DLB concept is applied to a test case implemented in the MDO framework HawtOpt2 [1, 15]. For brevity, only an overview of the design variables and constraints is reported in this paper (see Appendix B). For the full description of the problem formulation and workflow used, the reader can refer to [1, p.2-6]. In the present study, the load estimation part of the workflow is done using the reduced DLB and not the steady state calculation method reported in [1]. Unlike the problem reported in [1], the cost function is the maximization of the annual energy production. To achieve the objective, the blade can stretch, increasing the rotor diameter and the energy captured. The design is further challenged by adding the orientation of the fibres in the spar caps as design variables. The optimizer can exploit the bend-twist coupling toward feather, hence decreasing dynamically the angle of attack to control the loading on the wind turbine [24]. As the fibres in the spar caps start to rotate to create the structural coupling, the bending stiffness of the blade decreases. The blade design becomes more prone to ultimate failure due to the increase of the loading as the rotor diameter stretches to harvest more energy. Moreover, the rotation of the fibres in caps can compromise the tower clearance required by the standard. It is therefore important to be able to properly catch the variations of the loads along the blade span, so that the optimizer can vary the design to conveniently accommodate the strength and tower clearance requirements.

The aim of the MDO problem formulated is to reach an improved design exploiting the possibility of catching the quality of the load variations through the use of the reduced DLB approach. In fact, due to the simplification in the load analysis brought by the absence of turbulence, the optimization cannot identify a global optimum for the design chosen. For the time being, the achievement of a better design compared to the baseline is considered satisfactory, but future work on better methodologies to estimate aeroelastic loads in an MDO is going to be carried out. At time being, surrogate-based methods with the creation of an Approximation Model Management Frameworks (AMMF) are explored [25, 26, 27].

A standard full DLB is computed on the optimal design coming out of the MDO. The wind turbine design characteristics and requirements such as AEP, tower clearance, and fatigue loads reported in Appendix C Table C1 and Figure C1 are hence extracted from a full DLB to show the ability of the reduced DLB to respect the design requirements set for the optimization.

The final design has a longer blade radius and, consequently, the wind turbine has a higher AEP (+4.4%). The blade mass is slightly increased (+1.2%) to sustain the higher loading and improve the strength of the blade, counteracting the negative effects caused by turning the fibres of the uniaxial material in the caps. The tower clearance requirement is kept within the given constraints. Table C1 in Appendix C shows a summary of these characteristics with respect to the original design.

In Appendix C, Figure C1 provides an overview of the strength and loads of the final design obtained from the MDO process. The plot on the left shows the maximum failure indices for each cross section along the blade. The failure indices are evaluated applying loads obtained from a full standard DLB simulated at the end of the optimization on the final design. The

ultimate loads are selected from the envelopes projecting flapwise and edgewise moments in twelve directions (not only in four directions as done in Figure 3). The reduced DLB is able to drive the ultimate loads calculation in the right direction during the MDO, as the final design can withstand a full DLB ultimate loads respecting the given constraints. In fact, no failure is detected along the blade according to the strain criteria.

In Appendix C Figure C1, the plot on the right shows the variation of life-time equivalent fatigue moments for the blade root and tower registered for the optimal design. Even though no constraints were put to control these loads, the bend-twist coupling effect generated by the material structural coupling helps to contain the increase. Figure C2 in Appendix C shows the bend-twist coupling parameter along the blade length. The flap-wise bending-twist coupling coefficient β is calculated along the blade length in accordance to the method described in [28]. Except for the blade root torsional moment which increases by approximately 15%, all the other fatigue loads register a maximum increase of approximately 4%. To improve these results even further, constraints on fatigue loads are going to be included in future studies. The fatigue loads constraints are going to be computed using the method described in [29] and already used for optimization in [1].

6. Conclusions

The estimation of ultimate load envelopes is a central topic for wind turbine blade design. The calculation of these envelopes requires a great computational effort, which cannot be practically integrated into multidisciplinary design optimization frameworks. The solutions proposed in recent years to calculate ultimate loads in wind turbine blade optimization do not allow the use of design variables that have a large impact on the distribution of the loading along the blade, i.e. blade sweep and orientation of the fibres in the layups. With the approach suggested by this study, the estimation of the ultimate blade load envelopes can be fast and accurate enough to be used in each cost function evaluation of an MDO. This approach is based on the formulation of a deterministic reduced DLB that can be computed quickly even by a "slow" aero-servo-elastic code. As the stochastic effect of turbulence might have dangerous consequences during an optimization process, the reduced DLB mimics the influence of turbulence on loading through a deterministic approach.

Results show that the ultimate load envelopes generated by the full and the reduced DLBs are similar, and the ultimate loading projected in the flapwise and edgewise directions vary along the same path.

An applied case study was reported, showing a design optimization process for the DTU 10 MW RWT blade. Blade radius and spar caps fibre orientation were included as design variables. The final optimal design is checked against a full standard DLB. An accurate estimation of the ultimate loads through the use of the reduced DLB at every cost function evaluation, produced a final design able to increase the AEP by 4.4%, withstanding increasing ultimate loads and without compromising the tower clearance. Life-time equivalent fatigue loads are not excessively incremented thanks to the material induced bend-twist coupling effect.

The MDO problem cannot spot a global optimum due to the simplified load analysis approach. The reduced DLB method can give a good estimation of the quality of the variations in loading, but not an accurate estimation of their magnitude. Future work is going to address different methodologies, such as surrogate-based methods including AMMF, to include accurate aeroelastic loads in an MDO with very fast computations.

Acknowledgements

References

[1] Zahle F, Tibaldi C, Verelst D R, Bak C, Bitche R and Blasques J P A A 2015 Aero-elastic optimization of a 10 mw wind turbine *Proceedings - 33rd Wind Energy Symposium* vol 1 (American Institute of Aeronautics and Astronautic) pp 201–223

[2] Bottasso C L, Campagnolo F and Croce A 2012 Multi-disciplinary constrained optimization of wind turbines *Multibody System Dynamics* vol 27 (Springer) pp 21 – 53 ISSN 1573-272X doi: 10.1007/s11044-011-9271-x

[3] Fuglsang P, Bak C, Schepers J, Bulder B, Cockerill T, Claiden P, Olesen A and Rossen R 2002 Site-specific design optimization of wind turbines *Wind Energy* vol 5 (John/Wiley and Sons Ltd.) pp 261–279 ISSN 1095-4244 doi: 10.1002/we.61

[4] Ashuri T, Zaaijer M B, Martins J R R A, van Bussel G J W and van Kuik G A 2014 Multidisciplinary design optimization of offshore wind turbines for minimum levelized cost of energy *Renewable Energy* vol 68 (Elsevier) pp 893–905 doi: 10.1016/j.renene.2014.02.045

[5] Ning S A, Damiani R and Moriarty P J 2014 Objectives and constraints for wind turbine optimization *Solar Energy Engineering* vol 136 (ASME) doi: 10.1115/1.4027693

[6] Bak C, Zahle F, Bitsche R, Kim T, Yde A, Henriksen L C, Natarajan A and Hansen M H 2013 *Description of the DTU 10 MW Reference Wind Turbine* (Roskilde, Denmark: DTU Wind Energy, Technical Report-I-0092)

[7] Hansen M H, Thomsen K, Natarajan A and Barlas A 2015 *Design Load Basis for onshore turbines - Revision 00* (Roskilde, Denmark: DTU Wind Energy, Technical Report E-0074(EN))

[8] DTU Wind Energy Hawc2 URL `http://www.hawc2.dk/`

[9] Larsen T J and Hansen A M 2015 *How 2 HAWC2, the user's manual* DTU Wind Energy Risø-R-1597(ver.4.6)(EN), Roskilde, Denmark

[10] Kim T, Hansen A M and Branner K 2013 Development of an anisotropic beam finite element for composite wind turbine blades in multibody system *Journal of Renewable Energy* vol 59 (Elsevier) pp 172–183 doi: 10.1016/j.renene.2013.03.033

[11] Larsen T J, Madsen H A, Larsen G C and Hansen K S 2013 Validation of the dynamic wake meander model for loads and power production in the egmond aan zee wind farm *Journal of Wind Energy* vol 16 pp 605–624 doi: 10.1002/we.1563

[12] Popko W, Vorpahl F, Zuga A, Kohlmeier M, Jonkman J, Robertson A, Larsen T J, Yde A, Stertr K and et al K O Offshore code comparison collaboration continuation (oc4), phase i - results of coupled simulations of an offshore wind turbine with jacket support structure *Proceedings of the International Offshore and Polar Engineering Conference 2012* pp 337–346 rhodes, Greece, 17-23 June 2012

[13] Vorpahl F, Strobel M, Jonkman J M, Larsen T J and Passon P 2013 Verification of aeroelastic offshore wind turbine design codes under iea wind task xxiii *Journal of Wind Energy* doi: 10.1002/we.1588

[14] Hansen M H and Henriksen L C 2013 *Basic DTU Wind Energy Controller* (Roskilde, Denmark: DTU Wind Energy, Technical Report-E-0018)

[15] Zahle F, Tibaldi C, Verelst D R, Bak C, Bitche R and Blasques J P A A 2015 *Rotor Design Optimization Tools and Cost Models* (Bremen, Germany: IQPC Workshop for Advances in Rotor Blades for Wind Turbines) URL `http://orbit.dtu.dk/files/115528875/iqpc_hawtopt2.pdf`

[16] NASA Glenn Research Center Openmdao URL `http://openmdao.org`

[17] Moore K, Naylor B and Gray J 2008 The development of an open-source framework for multidisciplinary analysis and optimization *10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Victoria, Canada* (AIAA)

[18] Gray J S, Moore K T and Naylor B A 2010 Openmdao: An open source framework for multidisciplinary analysis and optimization *13th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Fort Worth, Texas* (AIAA)

[19] Heath C M and Gray J S 2012 Openmdao: Framework for flexible multidisciplinary design, analysis and

optimization methods *8th AIAA Multidisciplinary Design Optimization Specialist Conference (MDO), Honolulu, Hawaii* (AIAA)

[20] Perez R E, Jansen P W and Martins J R R A 2012 pyOpt: A Python-based object-oriented framework for nonlinear constrained optimization *Structures and Multidisciplinary Optimization* vol 45 (Springer) pp 101–118

[21] Gill P E, Murray W and Saunders M A 2002 Snopt: An sqp algorithm for large-scale constrained optimization *Journal on Optimization* vol 12 (SIAM) pp 979–1006

[22] Tibaldi C, Henriksen L and Bak C 2014 Investigation of the dependency of wind turbine loads on the simulation time *proceedings of EWEA 2014* (European Wind Energy Association (EWEA))

[23] Internation Electrotechnical Commission 2005 *International Standard, IEC 61400-1 Third Edition 2005-08, Wind Turbines - Part 1: Design Requirements* (Reference Number IEC 61400-1:2005(EN))

[24] Bottasso C, Campagnolo F, Croce A and Tibaldi C 2013 Optimizationbased study of bendtwist coupled rotor blades for passive and integrated passive/active load alleviation *Wind Energy* vol 16 (John/Wiley and Sons Ltd.) pp 1149–1166 ISSN 1095-4244 10.1002/we.1543

[25] Koziel S, Ciaurri D E and Leifsson L 2011 Surrogate-based methods *Computational Optimization, Methods and Algorithms - State of the art in Computational Optimization* vol 356 ed Koziel S and Yang X S (Springer-Verlag Berlin Heidelberg) pp 33–59 iSBN: 978-3-642-20859-1

[26] Simpson T, Toropov V, Balabanov V and Viana F 2008 Design and analysis of computer experiments in multidisciplinary design optimization: A review of how far we have come - or not *Multidisciplinary Analysis Optimization Conferences* (American Institute of Aeronautics and Astronautics) pp – URL `http://dx.doi.org/10.2514/6.2008-5802`

[27] Queipo N V, Haftka R T, Shyy W, Goel T, Vaidyanathan R and Tucker P K 2005 Surrogate-based analysis and optimization vol 41 pp 1 – 28 ISSN 0376-0421 URL `http://www.sciencedirect.com/science/article/pii/S0376042105000102`

[28] Fedorov V and Berggreen C 2014 *Bend-twist coupling potential of wind turbine blades* vol 524 (Institute of Physics Publishing) ISSN 1742-6596

[29] Tibaldi C, Henriksen L, Hansen M and Bak C 2015 Wind turbine fatigue damage evaluation based on a linear model and a spectral method *Wind Energy* vol 18 (John/Wiley and Sons Ltd.) ISSN 1095-4244 10.1002/we.1898

Appendix A. Reduced Design Load Basis Overview

Table A1: List of the DLCs included in the reduced design load basis used for the baseline wind turbine design.

Name	Description	WSP [$\mathrm{m\,s^{-1}}$]	Yaw [°]	Shear	Gust	Fault	Nr. Cases
DLC11	Normal production	4:2:26	0	Eqs. 1-2	None	None	12
DLC13	Normal production	4:2:26	0	Eqs. 1-3	None	None	12
DLC14	Normal production	$V_r \pm 2, V_r$[a]	0	0.2	EDC[b]	None	3
DLC15	Normal production	4:2:26	0	0.2	EWS[c]	None	48
DLC21	Grid loss	4:2:26	0	Eqs. 1-2	None	Grid loss at 10s	12
DLC23	Grid loss	$V_r \pm 2, V_r$	0	0.2	EOG	Grid loss at 3 times	12
DLC24	Large yaw error	4:2:26	-20/+20	Eqs. 1-2	None	Large yaw error	24
DLC32	Start-up at 4 times	V_{in}[a]$, V_r \pm 2, V_{out}$[a]	0	0.2	EOG	None	16
DLC33	Start-up in EDC	$V_{in}, V_r \pm 2, V_{out}$	0	0.2	EDC	None	16
DLC42	Shut-down at 6 times	$V_r \pm 2, V_{out}$	0	0.2	EOG	None	18
DLC51	Emergency shut-down	$V_r \pm 2, V_{out}$	0	Eqs. 1-2	None	None	3
DLC61	Parked, extreme wind	V_{50}[d]	-8/+8	0.11	EOG	None	2
DLC62	Parked grid loss	V_{50}	0:15:345	0.11	EOG	Grid loss	24
DLC63	Parked large yaw error	V_1[e]	-20/+20	0.11	EOG	Large yaw error	2
DLC71	Rotor locked extreme yaw	V_1	0:15:345	0.11	EOG	Rotor at 0:30:90°	72
DLC81	Maintenance	V_m[f]	-8/+8	0.2	EOG	Maintenance	2
						Total	278

[a] V_r, V_{in}, and V_{out} are the rated, cut-in, and cut-out wind speeds, respectively.
[b] Extreme direction change [23, p. 27].
[c] Extreme wind shear [23, p. 30].
[d] V_{50} is the extreme wind speed with 50-year recurrence period [23, p.25-26].
[e] V_1 is the extreme wind speed with 1-year recurrence period [23, p.25-26].
[f] V_m is the maintenance wind speed.

Appendix B. DVs and Constraints Overview for Case Study Section 5

Table B1: Free form deformation spline (FFD) used in the optimization to define the blade design variables. The spanwise distribution is normalized with respect to the blade length.

Design Variables	CPs Spanwise Distribution	DVs	Comment
Planform $\mathbf{x}_p$			
Blade length		1	Blade stretches.
Twist	[0.25, 0.45, 0.65, 0.9, 1]	5	Blade root fixed.
Blade pre-bend	[0.45, 0.65, 0.9, 1]	4	Blade root fixed.
Structure $\mathbf{x}_s$			
Spar Caps Uniax (SCU)	[0., 0.2, 0.45, 0.75, 0.95, 1.]	5	Pres./suc. side.
SCU fibre angle, pressure side.	[0., 0.2, 0.45, 0.75, 0.95, 1.]	5	[-20°, +20°]
SCU fibre angle, suction side	[0., 0.2, 0.45, 0.75, 0.95, 1.]	5	[-20°, +20°]
Total		25	

Table B2: Constraints used in the MDO process.

Constraints	Value	Cons	Comment
Planform g			
max(pre-bending)	< ref. value	6	Maximum pre-bending limited according to scaled blade radius.
Structural $\mathbf{h_g}$			
min(blade mass)	< 1.05	1	The blade mass can increase by 5% compared to the one of the DTU 10MW RWT.
min(blade mass moment)	< 1.05	1	The blade mass moment can increase by 5% compared to the one of the DTU 10MW RWT.
min(material thickness)	> ref. value	10	Ensure that the layups have realistic thicknesses depending on section region and material.
$t/w_{sparcap}$	> 0.08	38	Constraint for spar cap buckling.
Strength $\mathbf{h_s}$			
Ultimate strain criteria	< 1.0	190	Material failure in each region of each blade section for ultimate load cases.
Aeroelastic k			
min(tower clearance)	> ref. value	1	Standard minimum tower clearance.
Total		267	

Appendix C. Results for Case Study Section 5

Table C1: Overview of the general characteristics of the final optimized design. Results are shown in percent variation from the baseline design.

	Variation from Baseline
Blade radius	+7.7%
Blade mass	+1.2%
Blade tip pre-bending	+85.8%
AEP	+4.4%
Tower Clearance	+2.1%

(a) Max sectional failure indices

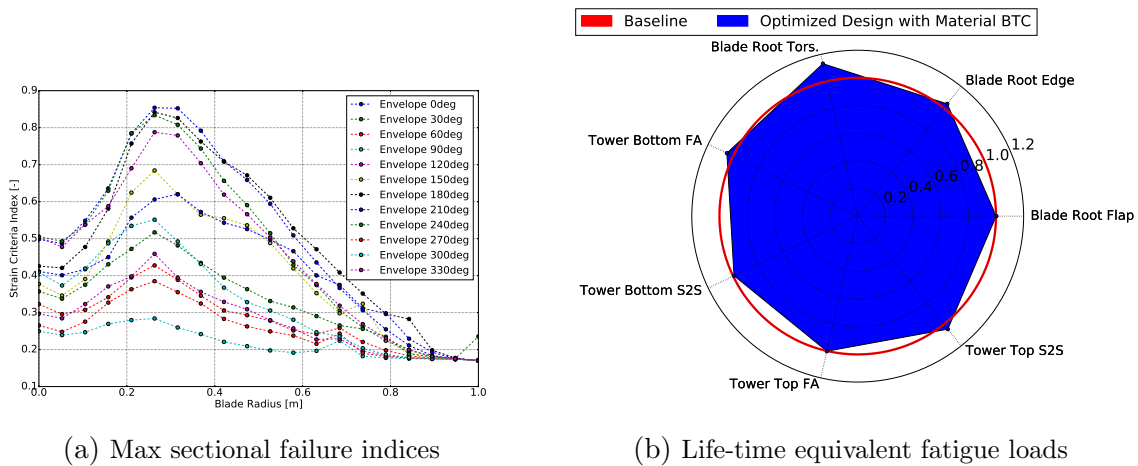(b) Life-time equivalent fatigue loads

Figure C1: Maximum sectional failure indices (a) and life-time equivalent fatigue loads (b) reported in radar-chart plots. Failure indices are computed for twelve load cases extracted from ultimate sectional blade load envelopes. Fatigue load results are provided for the following sensors: blade root, tower top, and tower bottom. The optimal blade design (blue) is normalized with respect to the baseline loads (red line). "FA" stands for fore-aft, "S2S" for side-to-side, and "Tors." for torsional.
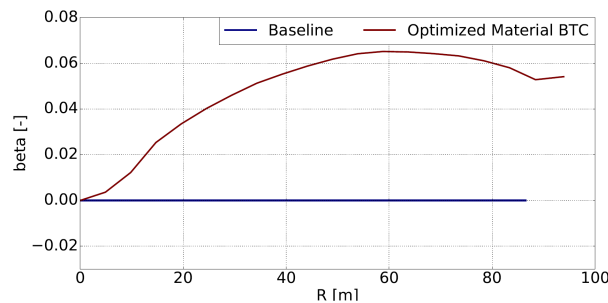

Figure C2: Bend-twist coupling parameter along the blade span.