Reduction of fatigue loads on jacket substructure through blade design optimization for multi-megawatt wind turbines at 50 m water depths

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1 - Abstract

This paper addresses the reduction of the fatigue damage for multi-megawatt offshore wind turbines mounted on jacket type substructures at 50 m water depths. The study investigates blade design optimization of a reference 10 MW wind turbine under standard wind conditions of onshore sites. The blade geometry and structure are optimized to yield a design that minimizes tower base fatigue loads without significant loss of power production compared to that of the reference setup. The resulting blade design is then mounted on a turbine supported by a jacket and placed under specific offshore site conditions. The new design alleviates fatigue damage equivalent loads in the jacket members, showing the possibility to prolong its design lifetime or to save material in comparison to the reference jacket. Finally, the results suggest additional benefit on the efficient design of other components such as the constituents of the nacelle.

2 - Environmental conditions, Structures, and Simulations

- The environmental data are the site specific conditions as found in [3].
- The wind turbine is a variable speed pitch controlled conceptual offshore wind turbine whose rated power is 10 MW [2].
- The reference jacket has been developed within the INNWIND.EU project [3] for the said reference turbine.
- The aero-hydro-servo-elastic simulations are carried out with the software package HAWC2 [1].
- The IEC DLC 1.2 NTM [4] has been used for load assessment:
  - 11 mean wind speed bins; one turbulence seed each;
  - 16 primary wind direction, plus $\pm 8^o$ yaw error;
  - Pierson-Moskowitz wave spectrum type, aligned with wind directions.

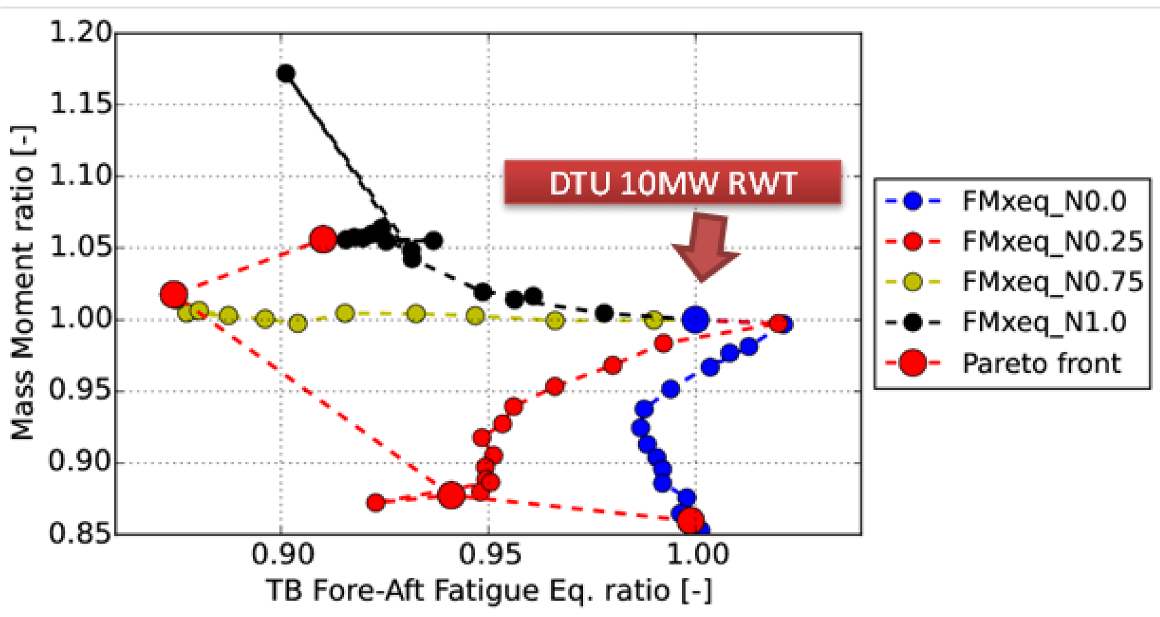
3 - Blade design optimization

$$f(\{x_p, x_s\}, p, w) = (1-w)\frac{M_m(\{x_p, x_s\}, p)}{M_m(\{0,0\}, p)} + w\frac{DEL(\{x_p, x_s\}, p)}{DEL(\{0,0\}, p)}$$

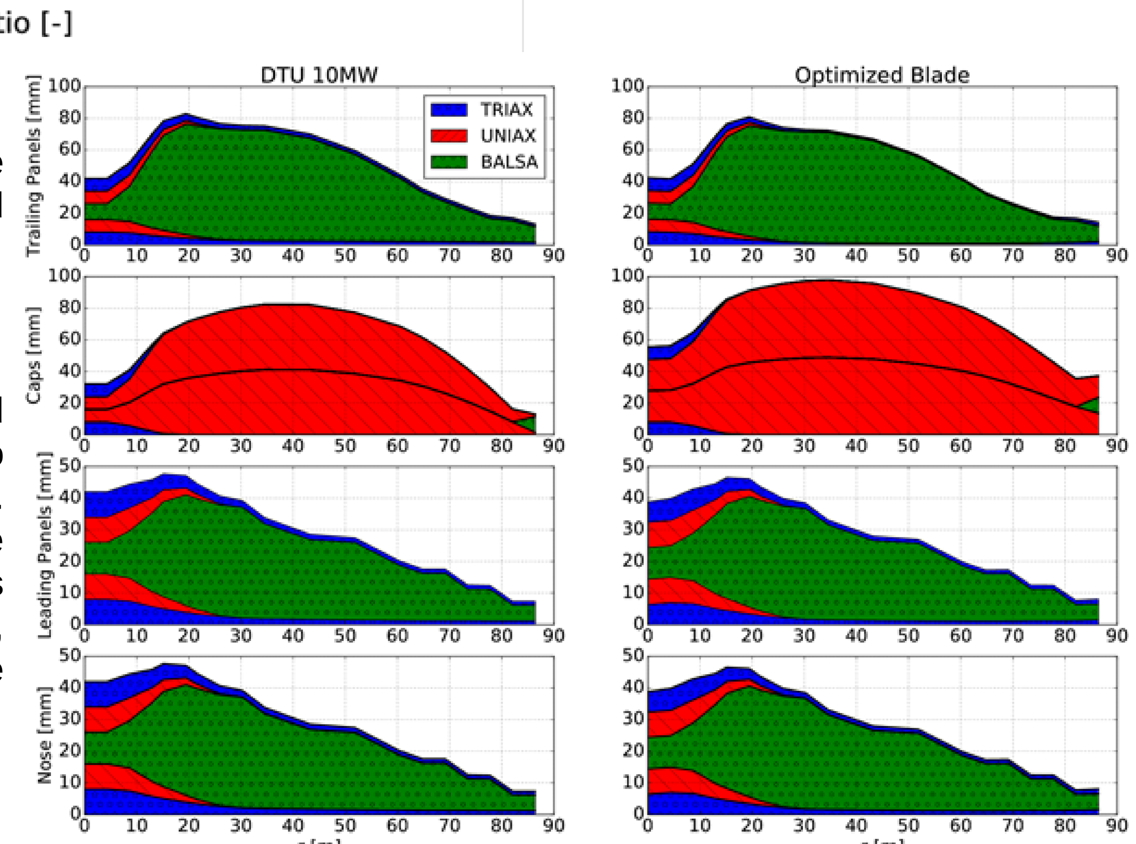
The objective function, f, depends on a set of planform variables x_p, a set of structural variables x_s, a set of constant parameters $\mathbf{p}$, which includes all the characteristics of the 10 MW wind turbine, and a weight w, that defines toward which of the elementary objectives the optimization is biased; $M_m(\{\mathbf{0},\mathbf{0}\}, \mathbf{p})$ is the reference blade mass moment; $DEL(\{\mathbf{0},\mathbf{0}\}, \mathbf{p})$ is the reference tower base fore-aft damage equivalent load.

The constraints of the optimization problem include various criteria:
Planform – **Cross sectional geometry** – **Strength** – **Aeroelasticity**

4 - Blade design Results



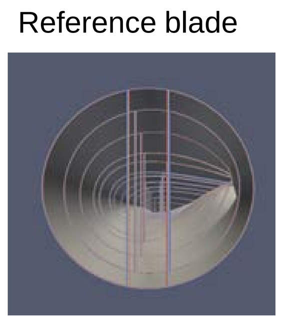
Pareto front for optimization of the DTU 10 MW RWT blade. The objective function aims at minimizing tower base fore-aft LTEFL and at minimizing blade mass moment. The compound objective is biased according to 4 weights: 0.0, 0.25, 0.75, 1.0, where 0.0 is full minimization of the blade mass moment.



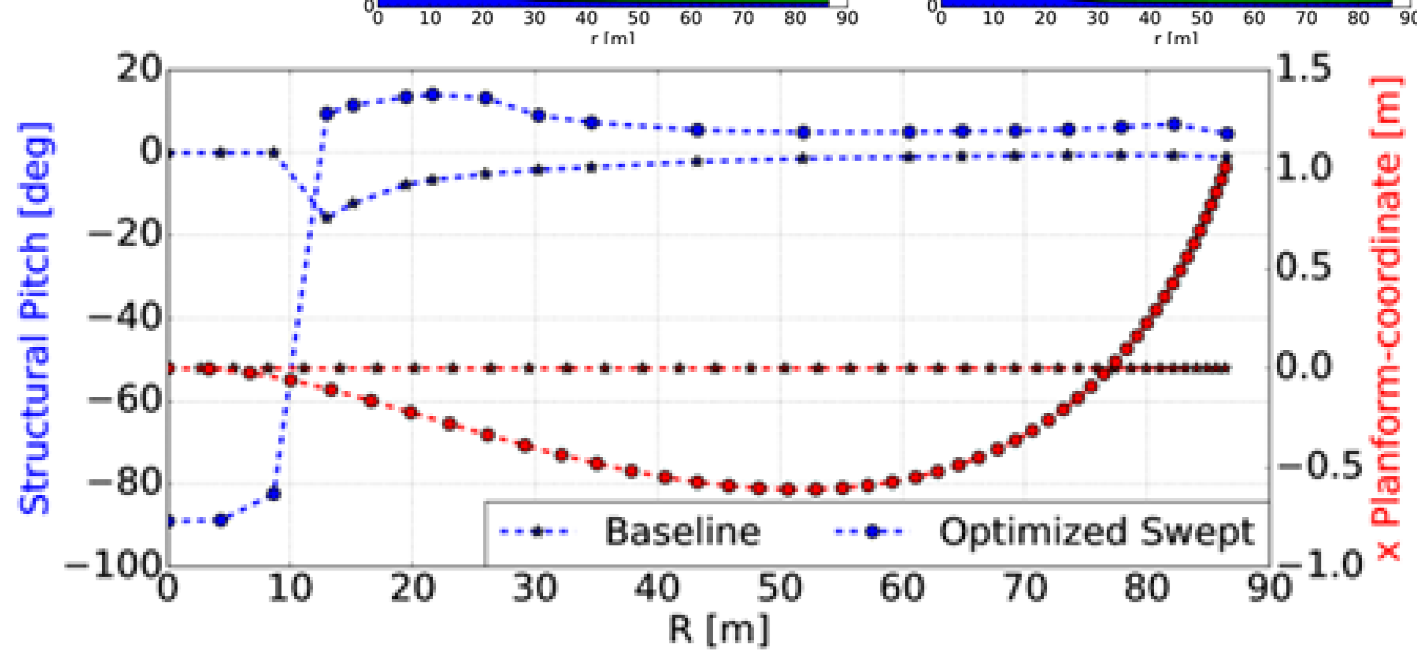
Comparison between the baseline blade layups (left) and optimized blade layups (right).

Comparison between baseline and optimized blade. (Left) close up to highlight the location of the caps. (Right) comparison between the blade geometries. Blue dashed lines represent the structural pitch axis, while the red ones is the x-coordinate of the centreline.

Reference blade

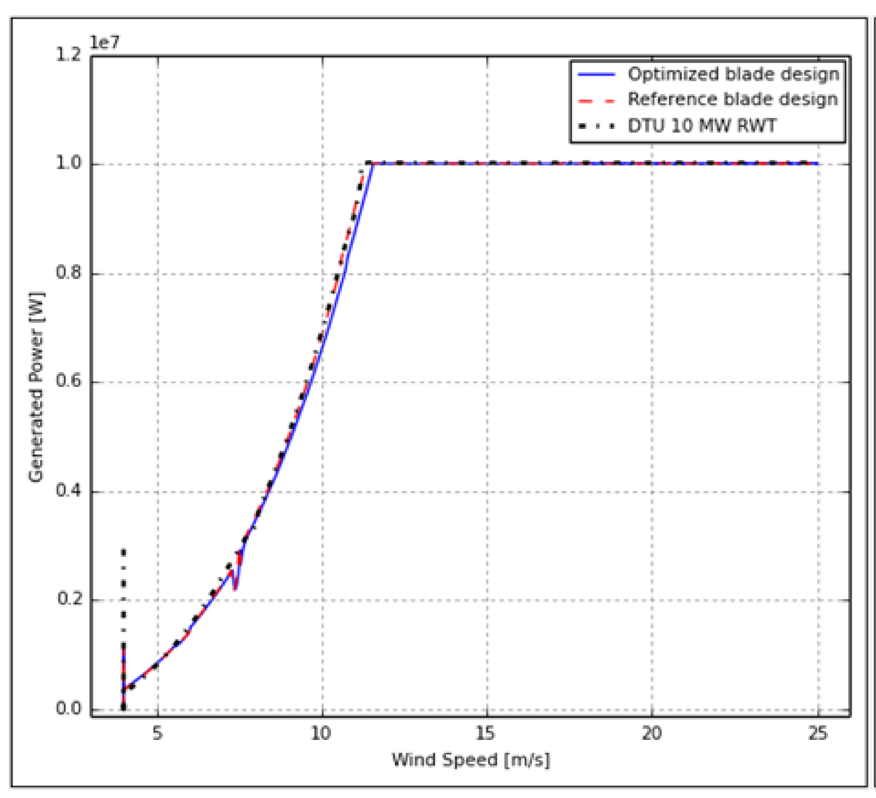


Optimized blade

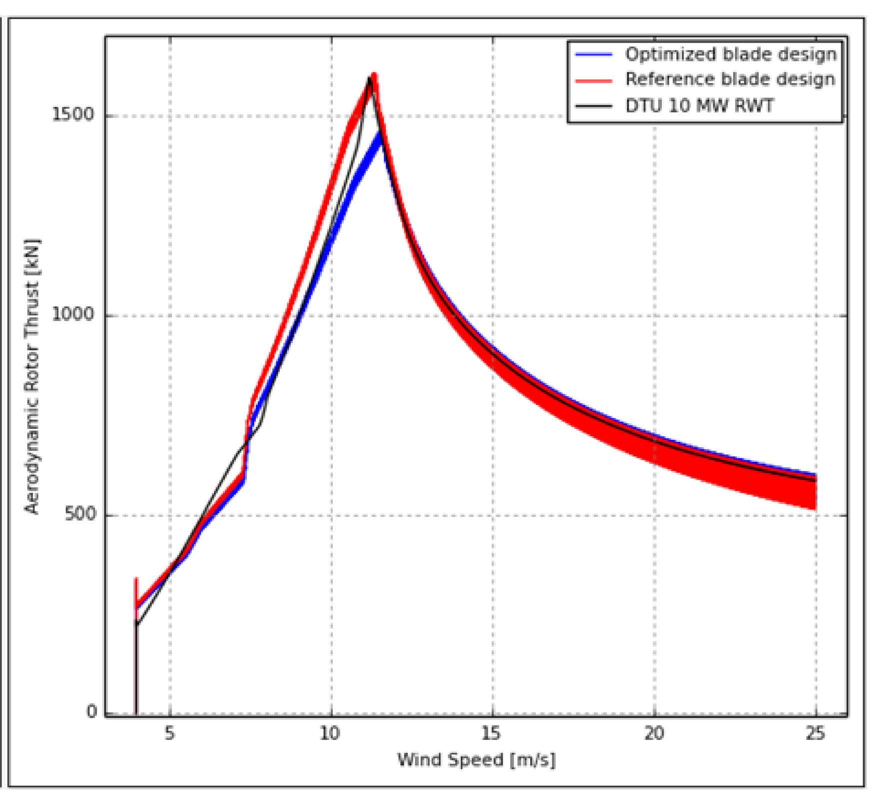


5 - Performance check

Power curves



Aerodynamic rotor thrust curves



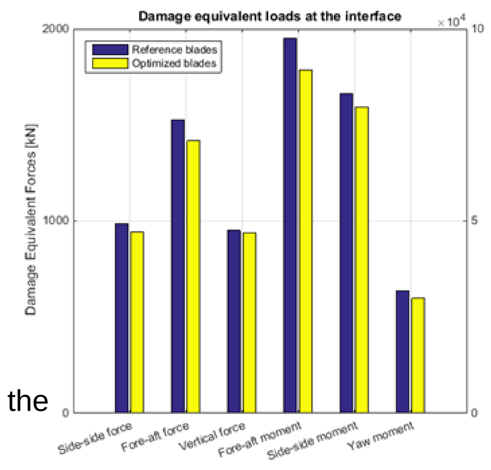
6 – Fatigue load reduction and Fatigue lifetime extension

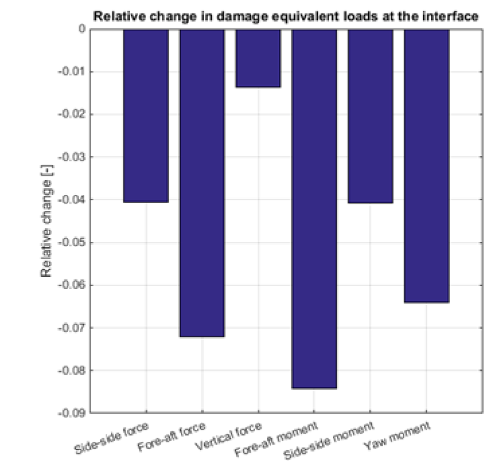
$$L_{eq} = \int_{V_{in}}^{V_{out}} p(V) \int_{\Delta L_a}^{\Delta L_b} \left(\frac{n(\Delta L|V)\Delta L^m}{N_{eq}}\right)^{1/m} \mathrm{d}\Delta L\, \mathrm{d}V$$

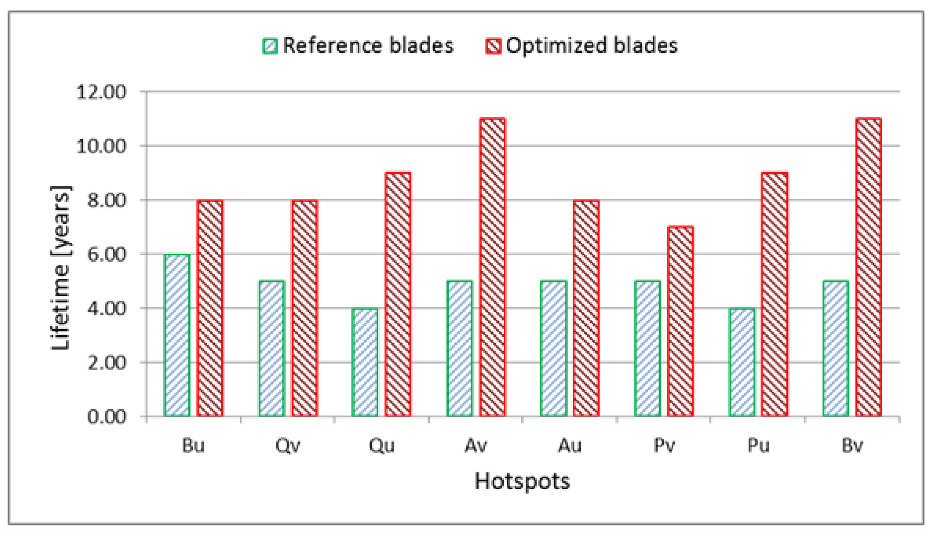
$$D_1 = \gamma_{DF}\frac{T_1}{T}\int_{V_{in}}^{V_{out}}\int_{\Delta\sigma_A}^{\Delta\sigma_B} \frac{n(\Delta\sigma|V,T)}{N(\Delta\sigma)} p(V)\, \mathrm{d}\Delta\sigma\, \mathrm{d}V$$

$\boldsymbol{N_{eq}}$ is the equivalent number of cycles during the structure lifetime, $N_{eq} = 10^7$;
$\boldsymbol{m}$ is the Wöhler parameter, $m = 4$;
$\boldsymbol{\gamma_{DF}}$ is the fatigue reserve factor associated with lack of possibility for inspections, $\gamma_{DF} = 3.0$;
$\boldsymbol{T_1}$ is the number of seconds in one year
$\boldsymbol{T}$ is the simulation duration, $T = 600\ s$;
$\boldsymbol{N(\Delta\sigma)}$ is the number of cycles that can cause full damage under the stress range $\Delta\sigma$,
$\boldsymbol{n(\Delta\sigma|V,T)}$ is the actual number of cycles corresponding to the stress range $\Delta\sigma$, given a wind speed V and the simulation duration T, and
$\boldsymbol{p(V)}$ is the probability of occurrence of the wind speed V.

The fatigue lifetime in years is obtained by $L_f = D_1^{-1}$







7 - Conclusion

- It is computationally efficient to carry out the optimization process on a (simple) land turbine subjected to standard wind conditions, and then to adapt the resulting design on a (complex) offshore turbine subjected to site specific metocean conditions.
- Altogether with the fore-aft fatigue moment, all other fatigue loads at the tower base as well as loads at the tower top have been alleviated without a significant loss of power production. The load reduction is beneficial to the efficient design of all wind turbine's modules, which include nacelle's components and support structure.
- The reduction of fatigue loads at the tower bottom resulted in fatigue lifetime extension at every selected hotspot, which allows material cost saving for the jacket substructure (which for an offshore turbine has the largest CAPEX contribution).

8 - Acknowledgement

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9 - Main References

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