Gradient based structural optimization of jacket structures with fatigue and ultimate limit state constraints for offshore wind turbines

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ABSTRACT

To accommodate the worlds increasing demand for sustainable energy, the offshore wind energy industry is advancing beyond shallow waters. Installing wind turbines further away from the coast will generally mean favorable wind conditions. However, it will also mean larger support structures due to an increase in depth, in overall mass, in aero-elastic loading, and in hydrodynamic loading.

In the context of structural design of support structures for offshore wind turbines, reliable and efficient computational methods for preliminary design can serve as a powerful design tool. Thus, the main objective of this work is to present and implement analytical design sensitivities for sizing optimization including both fatigue and ultimate limit state constraints based on international design recommendations. The key challenge is efficiently and correctly addressing the very large time-history loads and the large amount of constraints. Main emphasis in this work is on the fatigue constraints.

The established framework is demonstrated on the OC4 reference jacket with the NREL 5 MW reference turbine. The jacket is modeled using 3D Timoshenko beam elements, where the aero-elastic loads are determined using multibody simulation software and the hydrodynamic loads are determined using the Morison equation.

To reduce overall mass, the interconnected tubular members of the jacket are optimized with respect to diameter and thickness, while the overall topology of the structure remains. The tubes are subjected to ultimate limit state constraints based on Eurocode 3. These constraints are buckling, chord-face failure, and punching shear failure in all connections. Furthermore, there is enforced a frequency constraint ensuring that the natural frequency of the support structure is designed to be in the soft-stiff region, i.e. between the rotor and blade passing frequencies.

Fatigue failure is expected to occur in the welded connections. Thus, hot spot stresses are calculated using stress concentration factors in the cross sections of each connection as recommended by DNV. The stress amplitudes are found by performing rainflow counting individually in each of the stress evaluation points. The fatigue damage is determined by relating the stress amplitudes with S-N curves for structural steel submerged in seawater, and the accumulated damage is found using Palmgren-Miner's linear damage hypothesis.

The sensitivities of the cost function, the ultimate limit state constraints, and the frequency constraints are found using the direct differentiation method. The design sensitivity of the fatigue constraints is found using the adjoint method. This is counter intuitive as, generally speaking, the direct differentiation method is considered more effective when the amount of constraints are much larger than the number of design variables, which is the case. However, by utilizing linearity in the adjoint vector the fatigue sensitivities can be found efficiently. Thus, a relatively large amount of time-history loads can be included in the optimization problem, which is effectively solved using an SLP optimizer. The optimized design is compared with the initial design of the jacket.