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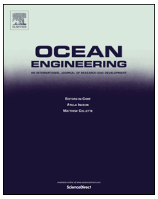

Two-stage local optimization of lattice type support structures for offshore wind turbines

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ABSTRACT

Offshore wind turbines are exposed to stochastic dynamic loading that includes non-linear aerodynamic effects. Hence, time domain simulations are needed for the analysis of support structures, resulting in a time consuming and computationally demanding optimization process. Here, the structural optimization was performed assuming that changing dimensions of a structural member does not affect other members of the structure, a heuristic based on the principle of domain decomposition. This allows for a simple sizing algorithm, which optimizes area and stress concentration factors element-wise using a meta-model for the structural performance. In order to further speed up the algorithm, designs were evaluated based on performance data from earlier analyses, while searching for the most suitable changes in design variables. This was found to be very efficient, resulting in a nearly full utilization of fatigue resistance and a saving of analysis time of roughly 40%. Randomly chosen initial designs initiated sequences that converged to the same minimum weight using fewer than seven structural analyses. Fatigue damage was the design driver in this analysis, while ultimate and buckling performance were controlled within the given constraints.

1. Introduction

Harvesting renewable energy by offshore wind turbines is expected to be an important energy source in the future (Hau, 2013). To be able to get a break through of this type of technology, the cost per kilowatt hour has to be reduced (Davey and Nimmo, 2012). One aspect of cost reduction is presented here: the computer-aided sizing process of a lattice type offshore wind turbine support structure using numerical simulations, leading to an optimized design with efficient utilization of the members.

Structural optimization has been used in automotive and aerospace industry for a long time, but to a lesser extent in the wind industry (Muskulus and Schafhirt, 2014). Most existing optimization approaches have been developed for static loading, whereas the structural analysis of wind turbines is more challenging due to a highly dynamic load picture. Fig. 1 illustrates the characteristics of the input loading acting on an offshore wind turbine. Due to the stochastic nature of turbulent wind and irregular wave loading (Naess and Moan, 2013), analytic solutions of the equations of motion are impracticable. Loads with various characteristics are acting on different parts of the structure, leading to excitations of the coupled system. As the wind turbine is exposed to the wind, resulting in a rotational movement of the rotor, the structure experiences additional loading frequencies. The rotor rotation is furthermore regulated by a control system, preventing damage for wind speeds above rated speed (normally around 12 m/s) and optimizing power production for lower wind speeds. Summing up, an offshore wind turbine is a highly dynamic, elastic and coupled system, subject to stochastic loading and control mechanisms. This results in the need of fully coupled time domain analyses, which require time consuming simulations compared to static load investigations. In the context of optimization, which normally requires several iterations to obtain an optimized design, this is an undesirable situation. Efficient optimization approaches for the time domain are needed. Some examples for such an application can be found in the literature, using gradient based methods (Ashuri, 2012; Chew et al., 2015b; Oest et al., 2015) or a genetic algorithm (Pasamontes et al., 2014). These methods vary significantly in the number of iterations needed, as well as the total computation time. Due to practical limitations with time domain analyses, significant simplifications in the load case assessment are normally performed for these methods.

In an effort to reduce the computational cost for detailed analyses, an efficient optimization approach using the principle of decomposition described by Freeman and Newell (1971) and Chandrasekaran (1990) is proposed and evaluated here. The method is based on the idea of a decomposition of the structure

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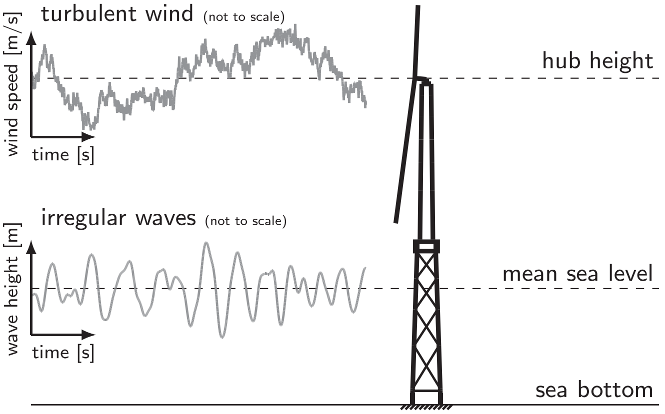

Fig. 1. Offshore wind turbine model with representation of input loading time series.

into weakly coupled substructures. Thereby, each member of the complete structure is optimized locally and simultaneously, assuming that other members of the structure are not affected by a change of member dimensions (Haftka and Gürdal, 1991). This eliminates the need for gradient based algorithms which are normally the method of choice for this type of structural optimization problem (Choi and Kim, 2005; Arora, 2011; Chew et al., 2015a). This so-called "local optimization" approach has been applied for the sizing of a full-height lattice tower in an iterative process earlier, but under the simplification of analyzing one power production load case only and with a heuristic for the changes in design variables that did not always lead to optimal designs (Zwick et al., 2012). The method of decomposition in the local optimization approach was now investigated in more detail with an improved algorithm and for a set of load cases that represent realistic load conditions for both ultimate and fatigue load analysis. Additionally, the method was now applied in a two-stage approach. Evaluation runs were performed by the finite element solver Fedem Windpower (Fedem Technology AS, Trondheim, Norway, Version R7.1.2) in a first stage. Fedem Windpower is a flexible multi-body solver for complex mechanical assemblies exposed to various loading and includes the functionality to calculate aerodynamic and hydrodynamic loads on the structure, as well as the capability to model a control system. Motivated by the intention of reducing the total computational effort needed for the structural optimization, the structural sizing process was performed in a second stage.

The sizing of structural members in the second stage was done with a meta-model for optimizing the member properties independently based on the structural performance. The sizing was carried out in an iterative manner. The second stage is therefore considered not to be the manipulation of the design variables itself, but the *iteration* of this manipulation without performing new evaluation runs with the finite element solver.

In this study, we present an analysis of the accuracy and validity of the proposed method for a representative set of load cases. It was found that the application of the local optimization approach is favorable and allows for a quick optimization of support structures. By using the heuristic principle of decomposition, the sizing method leads to an efficient utilization of the structural members in terms of fatigue damage, which was indicated to be the design driver in this analysis. The study also shows that the two stage approach further reduces the computational time.

2. Methodology

The following subsections describe the methodology used in this study. Details will be given for the simulation model, the applied loads, and the evaluation of structural performance, which has been carried out in terms of ULS, FLS, and buckling check. This section also describes the proposed local optimization approach and its two central assumptions.

2.1. Simulation model

The study has been performed with a generic offshore wind turbine with jacket support structure composed of the OC4 reference jacket (Vorpahl et al., 2011) and the well-known NREL 5-MW baseline wind turbine on top (Jonkman et al., 2009). Data for the environmental loads are taken from the UpWind design basis (Fischer et al., 2011). The following subsection will briefly summarize the main characteristics of the structural model and provide details about the environmental loads applied.

2.1.1. Wind turbine structure

The structural model used for the application of the local optimization is based on the OC4 reference jacket (Vorpahl et al., 2011). It is a four-legged lattice tower structure, consisting of four bays with X-brace side planes connecting the legs (Fig. 1). The connection to the tubular tower was modeled as a rigid transition piece made out of concrete. Placed on top of the tubular tower, the NREL 5MW baseline turbine defined by Jonkman et al. (2009) extracts energy from the wind. The model has been used and verified in earlier studies by Popko et al. (2014) and Zwick and Muskulus (2015).

Differing from the jacket definition by Vorpahl et al. (2011), the lattice structure was modeled with more features in this study. K- and X-joints (Fig. 2) were improved in detail by the introduction of chord cans and brace stubs. This technique is often used in offshore industry (Standards Norway, 2004) and enables a more efficient design that takes account of concentrated stresses in tubular joints, since structural properties of joints within the same bay can be individually adjusted (e.g. dimensions of the K-joint at height $z = -8.9$ m can differ to the dimensions of the K-joint at height $z = -24.6$ m, although both joints are members of the same bay). For K-joints, chord cans are oriented in leg direction, while stubs are oriented in brace direction (Fig. 2). For X-joints, two aligned members of the connected braces were treated as cans, while the connected members from the two other brace directions were treated as stubs. As a slight simplification, cans and stubs of X-joints had the same structural properties in this study and are further referred to as X-joint brace stubs only.

During optimization, cross sectional properties of all members were modified, while the topology remained the same as for the OC4 reference jacket. The structural properties of the jacket are described by five different cross section types (Table 1). Each type has several categories based on the number of in total 4 bays of the jacket structure, e.g., cross sections are independent from bay to

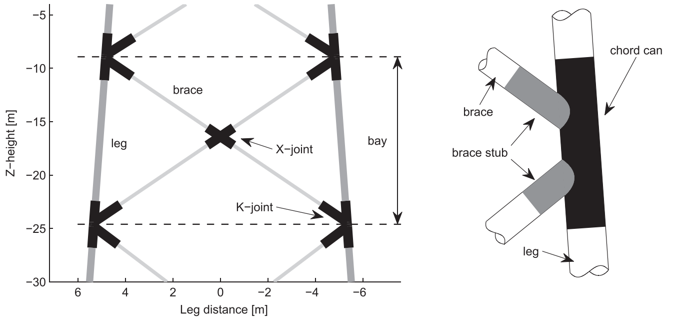

Fig. 2. Section of the jacket structure with details such as chord cans and brace stubs at K- and X-joints (proportions of legs, braces, chord cans and brace stubs not to scale).