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Design Optimization of Wind Turbine Support Structures—A Review

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Wind turbines are complex engineering systems, subject to highly fluctuating and irregular loads. The optimal design of wind turbines, in particular their towers, support structures and foundation systems, is a nontrivial task. Computer-aided approaches can significantly help in finding better and more economic solutions. In this short review, the challenges and possible approaches for structural optimization of wind turbines are highlighted, the existing literature is discussed, and recommendations are given for future work in this upcoming and highly relevant field of research.

INTRODUCTION

Structural optimization as a discipline has developed almost in parallel with the advancement of structural analysis (e.g., based on the finite element method). Formulating a design problem in a mathematically rigorous way allows for finding optimal solutions using semi-automatic and algorithmic solutions (Arora, 2012). The use of these methods has increased manifold with the decrease in the cost of computational resources and has opened up new ways of designing structures and systems. In contrast to a human designer and manual optimization – that all too often is limited to a very small number of design iterations – computer-aided optimization is able to search through a large number of possible scenarios and will also consider non-obvious solutions (Figs. 1 and 2). In particular, new innovative design solutions could be found.

These techniques are well known and highly utilized in the automotive and aerospace industry but surprisingly not so for the design of wind turbine structures. Whereas a lot of the knowledge and methods from the aerospace and helicopter industry have been adapted to wind turbine blade and rotor design, the design of wind turbine towers and support structures has seen few applications of such techniques, and there exist only a handful of studies considering system-level optimization of wind turbines.

On the one hand, this might be because the traditional tubular tower (onshore) and the monopile support structure (offshore) have been relatively straightforward to design, and a lot of experience has been accumulated in this area. On the other hand, new and more complex types of support structures have been considered offshore, especially for deeper waters (Twidell and Gaudiosi, 2009; EWEA, 2009; EWEA, 2011), and turbine size has also grown considerably, leading to more flexible turbines that are more prone to dynamic effects and excitation from both wind and wave loads. Another important consideration is that wind turbines are highly complex engineering systems. Their analysis is so specialized that there exist very few software and tools capable of simulating the complete turbine, and currently none of them perform simulations of a detailed wind turbine model faster than real-time. This need for specialized software means that common optimization frameworks and solutions are not readily transferred to wind turbine design.

Since the major goal of current wind energy research and development is significant cost reduction – of at least 20 percent by 2020, but preferably more (EWEA, 2005; The Carbon Trust, 2008; The Crown Estate, 2012) – the optimization of wind turbine structures is an important topic that should be high on the agenda of any funding agency. Although the support structure, tower and foundation only comprise around 17 percent of total capital costs, this is an area with a high potential for cost reduction (The Carbon Trust, 2008; The Crown Estate, 2012).

This short, specialized review considers structural optimization of wind turbine structures, with a focus on towers and support structures for offshore, bottom-fixed turbines. Specific challenges are highlighted, the existing literature is reviewed, and recommendations for future work are given. Since the methods for optimal design of land-based towers are similar, these are included in the discussion. Floating turbines pose unique additional challenges that are also addressed. Finally, a discussion of similar or more general approaches and studies (e.g., on rotor design and system optimization) is included for completeness, where illuminating. Throughout, we have tried to find and collect in a single document the most important references relevant for working with the optimization of wind turbine structures.

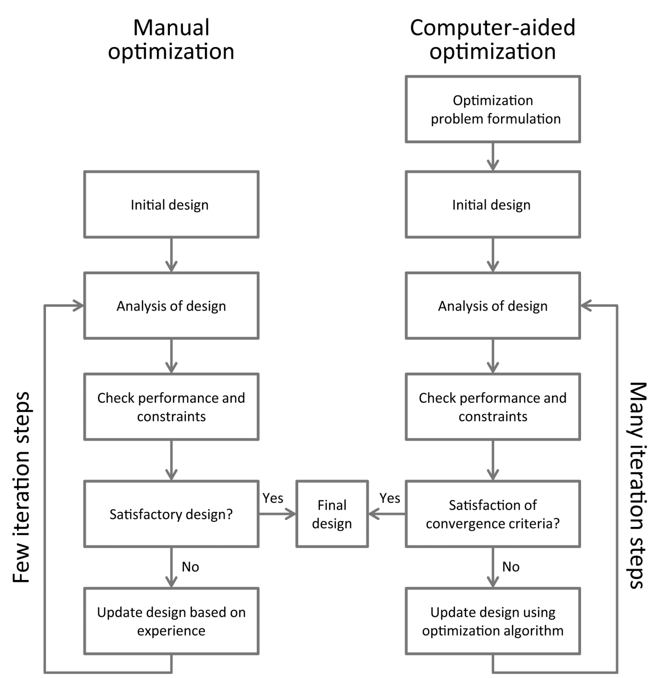

Fig. 1 Main steps, similarities and differences of manual and computer-aided optimization

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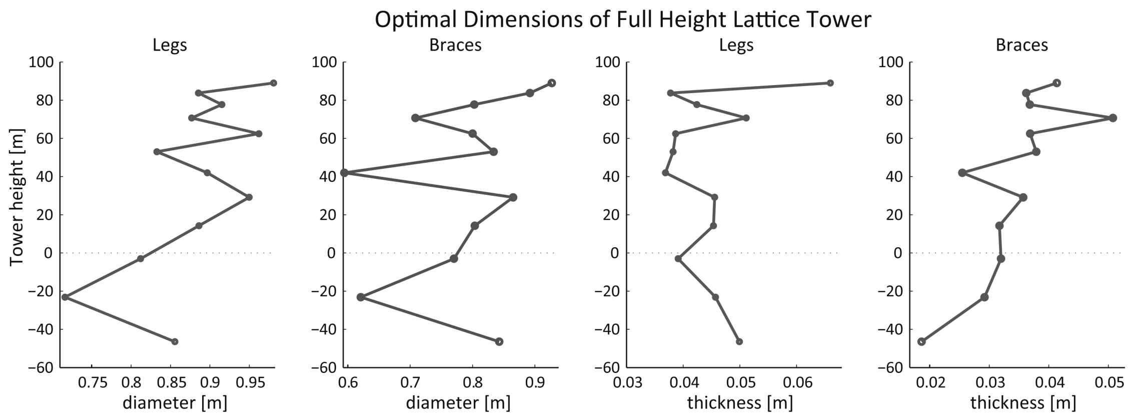

Fig. 2 Example for nontrivial design solution obtained during the automated optimization of a complex wind turbine support structure after 214 iterations (using the method from Molde et al., 2014). Both the diameter of legs and the thickness of braces are increasing almost linearly with height. These features are not what a human designer would typically use for such a structure. The oscillations in the dimensions are partly due to an existing relationship between parameters for legs and braces, namely, there exists a trade-off between brace and leg dimensions that can achieve similar utilization of joints for different choices of these parameters.

Specific Challenges

The design of wind turbine structures is challenged by the following six characteristic issues:

(1) Nonlinearities. Wind turbines exhibit nonlinear effects and time-history dependence, e.g., from unsteadiness in the flow and from structural nonlinearities. Examples of the former are wake development and its influence on induction factors (unsteady blade-element momentum theory), dynamic inflow, control algorithms, and stall-delay effects under pitch action (Quarton, 1999; Burton et al., 2011). Nonlinear wave loads (e.g., wave slamming/slapping loads) due to breaking waves in shallow water are another important issue (Alagan Chella et al., 2012). Regarding structural nonlinearities, the foundation typically contributes with significant nonlinearities, e.g., when using the general p-y method for piled foundations (API, 2010). Because of these effects, current standards prescribe that wind turbine analysis is performed in the time-domain (IEC, 2005; IEC, 2009; DNV, 2013).

(2) Complex environment. Wind turbines are subject to complex, irregular and highly fluctuating environmental conditions. The wind is turbulent and exhibits correlated spatio-temporal variations at many different scales, as well as coherent transient phenomena (such as gusts). For land-based turbines, understanding the interaction of the flow with complex terrain, and the characteristics of the wind field in the wake of other turbines, are active areas of research. Offshore turbines are additionally subject to wave loads and currents that, depending on the site conditions, consist of both viscous and inertial effects that are difficult to reconcile (Sarpkaya and Isaacson, 1981). Apart from uncertainty in parameters and coefficients, the irregular nature of the environment makes it necessary to simulate relatively long time-intervals in order to obtain sufficiently accurate results. Historically, wind turbines were analyzed with 10-min load cases to ensure sampling enough variability from the stationary loading process, but current standards for offshore wind turbines have recognized the need for better estimates and recommend at least 60 min of simulation time per load case, i.e., 6 x 10 min or 1 x 60 min in IEC (2009). In offshore engineering, for comparison, it has been common practice for many years to consider simulations of at least 3 hours, which is also relevant for floating wind turbines. Due to the wide range of environmental conditions typically encountered during the lifetime of a turbine, a large number of these load cases need to be analyzed. Additional effects due to scour, marine growth and sea ice might further complicate the loading.

(3) Fatigue as design-driver. The large number of cycles that a wind turbine rotor experiences during its lifetime means that wind turbine structures are exposed to a significant source of quasi-periodic excitations. The oscillatory wave action likewise causes significant quasi-periodic structural motions. Wind turbine structures are therefore prone to failure from fatigue damage, and fatigue assessment is mandatory. Unfortunately, this means that fatigue damage has to be extrapolated to the estimated lifetime of the wind turbine, which is 20 years in most projects. Combined with the long-term variability of the environment, this means that a large number of load cases need to be evaluated, typically in the order of a few thousand. Finally, whereas earlier wind turbine structures have often been designed with consideration of only global motions (i.e., motion of the structure in the first eigenmode), the observed increase in turbine size means that higher-order modes and localized phenomena have also become important. One example of such a phenomenon is vibrations of braces in jacket support structures, which can have a decisive effect on fatigue damage (Seidel et al., 2009; Böker, 2009).

(4) Specialized analysis software. The analysis of wind turbines is commonly based on numerical models and load simulations. These models include many different physical effects and loads. Capabilities for aerodynamic loads are provided by specialized load models (e.g., based on blade-element momentum theory), and only a handful of simulation codes provide this ability. Hydrodynamic analysis is likewise involved, and only a few tools exist that can perform both (Vorpahl et al., 2013). For onshore turbines, traditionally modal-based methods were used, but for jackets and other, more complex, offshore support structures, general finite-element capabilities are needed. The practical downside of these demands is that software is often not customizable or extendable and of limited functionality. Users can be hard pressed to find ways to perform non-standard analyses when the source code is unavailable or proper documentation is lacking, and the integration of the existing or new software tools into the users' workflow is difficult, since there exist few, if any, standardized interfaces or file formats. This is a particular challenge for collaboration among users with different software environments. Moreover, due to the complexity of the models, typical simulation times for realistic wind turbine design are slower than real-time, often significantly so.

(5) Tightly coupled and strongly interrelated systems. Wind turbines consist of many different parts and subsystems. The most computationally efficient manner would be to optimize each such part separately in a modular approach. This is simply not possible if, at the same time, high accuracy is sought. This issue is also reflected in the difficulty one has in quantifying wind turbine costs in a bottom-up manner. Material costs are relatively straightforward to estimate and use, but costs related to installation, operation and maintenance depend on many factors. These costs contribute significantly to the total project cost.

(6) Many design variables and constraints. Whereas onshore wind turbine towers and offshore monopiles can, to a large degree, be described by only a few parameters, modern multi-member support structure concepts (e.g., jacket structures) are characterized by many parameters and design variables. Even if the model is symmetric (such that, e.g., each bay in a jacket has the same type of legs or braces, with differences only between distinct bays), parameters typically number into the hundreds. This is normally not an issue for modern optimization algorithms that can deal with millions of parameters, but when the analysis is highly involved and time-consuming, this becomes a limiting factor. Moreover, since structural optimization problems are highly constrained and nonconvex, the objective function is usually multi-modal, i.e., exhibiting many local minima. It is therefore not straightforward to find a really optimal solution. This is well known from offshore engineering (Clauss and Birk, 1996).

STATE OF THE ART IN DESIGN OPTIMIZATION

Structural Optimization Under Static Loads

Structural optimization as a discipline has developed almost in parallel with the finite element method. It has focused considerably on finding the optimal solution(s) to static problems. The typical problem is to minimize the weight of a structure by varying parameters that define its geometry, i.e., diameters and thicknesses of structural elements. Alternatively, the stiffness of a structure is maximized. The *objective function* quantifies the degree by which the structure succeeds in fulfilling these objectives by a single numerical value (e.g., the total weight of the structure). This value depends in a fixed and predetermined way on the geometric parameters that describe the structure. Additional equations either describe fixed relationships between these parameters and other variables of the problem (*equality* or *inequality constraints*) or describe *side constraints* that restrict the range of parameters or solution variables within certain bounds. For example, diameters of steel pipes have both a minimum and maximum size due to manufacturing constraints. Also, installation methods and available vessels are limiting factors.

The mathematical structure of such an optimization problem is that of a nonlinear programming problem (Bertsekas, 1999; Arora, 2012). In general, these problems are hard to solve, and use is made of approximations and reductions to simpler problems as much as possible. In the special case where both the objective function and the constraint equations are linear or convex, the problem can be efficiently solved with methods from linear programming or convex optimization, respectively (Nocedal and Wright, 2006). In the general case, the problem is often solved by an iterative process, in which a number of convex approximations to the problem are solved. The basic method is called sequential linear programming, and common improvements or alternatives are called sequential quadratic programming, convex linearization, or the method of moving asymptotes (Christensen and Klarbring, 2009).

These methods, as well as more general search algorithms, are based on the availability of gradient information (Choi and Kim, 2005a; Choi and Kim, 2005b; Belegundu and Chandrupatla, 2011). Classical structural optimization therefore stresses the importance of what is often called *sensitivity derivatives* (Haftka and Gürdal, 1991) and constraint approximations. As optimization adds at least another order of magnitude to the computer time needed, there has always been a strong focus on approximations (Barthelmy and Haftka, 1993), fast reanalysis methods (Kirsch, 2010), and efficient evaluation of gradients (e.g., using the adjoint method and its variants). These methods become essential when considering large-scale structural models at the limits of current analysis capabilities. On the other hand, structural optimization problems with only a few parameters can often be solved analytically, which is extensively used in the optimization of single structural elements, e.g., in the determination of optimal cross-sections (Rees, 2009).

Optimization Under Transient Loads

The optimization of structures under transient loads is, in comparison with static optimization, less developed. The classical approach is *constraint-based*: in contrast to the static case, the constraints need to be respected at each time instant, i.e., the problem consists of an infinite number of constraint equations (Kang et al., 2006). In order to be solvable in practice, the time dependence is often removed by considering an integrated constraint (e.g., the integral sum of constraint violation over time), which has to be zero for a feasible solution. Alternatively, the constraint is evaluated at all critical points, i.e., the local minima of the constraint function that represent the instants in time where the constraint is closest to being violated (Haftka and Gürdal, 1991).

A problem with this class of problems is the calculation of sensitivity information. Numerical gradients based on finite differences are readily available but inefficient and unreliable. The method of *equivalent static loads* (ESL) reduces the problem to a number of static optimization problems, for which analytical gradients are easily obtained, and then combined to approximate the actual sensitivities (Kang et al., 2001; Park, 2007). Further advantages of this method are that it can be realized with most structural analysis software packages and that static response optimization can be performed with the ESL. Other techniques for determining gradients for time-dependent problems (dynamic load cases) are discussed by Choi and Kim (2005a, 2005b) and by Kennedy and Martins (2013).

More recently, dynamic optimization has been understood as avoiding structural eigenfrequencies where excitations exhibit significant energy, or to optimize the response due to sudden shocks (e.g., Cheng and Truman, 2010).

Optimization Under Fatigue Constraints

So far, the constraints were assumed to be generic, i.e., consisting of limits defined by material yield stress (ultimate limit state), buckling checks, manufacturing processes, etc. A rather important special class of constraints is given by the need to assess and limit fatigue damage of the structure.

Fatigue damage is typically evaluated by counting cycles in relation to their stress-ranges, using the rainflow counting algorithm with response time series obtained by dynamic analysis (Rychlik, 1987). The resulting cycle distribution is then integrated into a single damage or lifetime estimate by invoking the Palmgren-Miner linear damage rule with a material SN-curve. It is normally evaluated for specific hot spots (e.g., welded joints), using semi-empirical formulae that estimate the hot spot stresses from a number of nodal stress histories and the geometry (DNV, 2011).

Since most structures behave linearly for small displacements, as an alternative to time-domain simulation, frequency domain analysis and a semi-empirical estimation of fatigue damage can be performed, typically by using a model determined by fitting an extensive set of computer simulations (Dirlik, 1985). The process is readily automated and can also be performed for more complicated material behavior (El-Sayed and Lund, 1990).

Simulation-based Optimization

As indicated above, structural optimization with fatigue constraints is a challenging task. If the structure under consideration exhibits dynamic effects, such that changes in the geometry lead (under the same loading history) to significant differences in response histories, then it becomes almost impossible to use efficient analytical methods to obtain sensitivity information. Similarly, if maximum displacements and stresses are significantly affected by changes in geometry, then the evaluation of ultimate limit state constraints likewise hinders efficiently obtaining gradient information.

In such cases, where the objective function or the problem constraints are not amenable to efficient evaluation, a variety of methods from the field of simulation-based optimization can be employed (Gosavi, 2010). These less efficient techniques include methods based on meta-models, e.g., the Taguchi method (Roy, 2010) or general response-surface methods (Myers et al., 2009). See Angun (2008) for recent developments in dealing with expensive simulations. Other influential techniques include neuronal networks and genetic algorithms, or stochastic search and optimization approaches (Spall, 2003).

Probabilistic and Robust Optimization

The above techniques for optimization assume a deterministic objective function. Often, a probabilistic description of variability, uncertainty and sources of error (both from external influences and from internal issues with the numerical wind turbine model) is a more natural approach. Reliability-based design optimization and robust design optimization are two complementary approaches that allow for incorporating uncertainty and randomness in the design process (Tsompanakis et al., 2008). These methods are at least an order of magnitude more involved than "standard" structural optimization methods, since they involve nested analyses. They are closely related to the common lumping of environmental conditions into a discrete set of load cases (Kühn, 2001) and to the question of how partial safety factors are calibrated (Veldkamp, 2006). An application to the sizing of an offshore tripod structure has been reported by Karadeniz et al. (2009).

Ben-Tal et al. (2009) present the latest techniques for robust optimization, whereas Adeli and Sarma (2006) discuss fuzzy optimization.

OPTIMIZATION OF WIND TURBINE STRUCTURES

The Design Problem

Wind turbines are highly dynamic and tightly coupled systems, and their design poses specific challenges (Quarton, 1998; Petrini et al., 2010; Schaumann et al., 2011; Vorpahl et al., 2013). The rotor of a wind turbine is subject to aero-elastic effects that result in nonlinear, time-history dependent forces acting on the supporting structure (Fig. 3). The main sources of this excitation are the lift and, to a smaller degree, the drag forces on individual blade sections, as well as gravity and tower shadow loads (Burton et al., 2011). Due to the rotation of the blades, the force vectors are continuously rotating, which causes periodic fluctuations, mainly at the 1P (single blade passing) and 3P (rotor) frequencies. The aerodynamic forces depend strongly on the wind speed experienced by the blades, which is an irregular environmental condition characterized by turbulence and spatio-temporal correlations at various scales. For offshore turbines, hydrodynamic loads are a second source of irregular excitations that need to be taken into account when analyzing structural response.

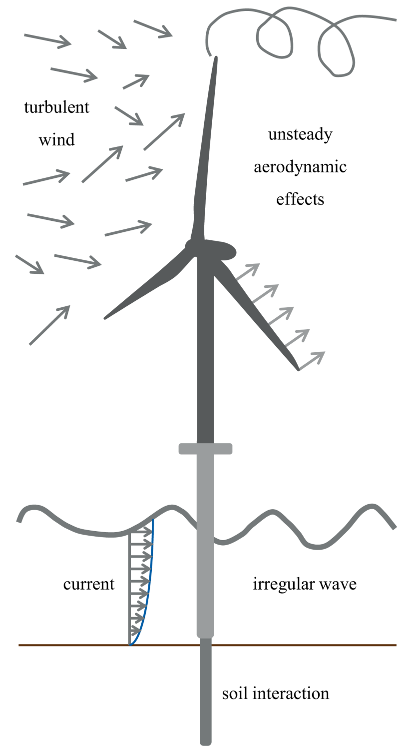

Fig. 3 Nonlinear and time-history dependent effects on an offshore wind turbine

The stochastic, irregular nature of the environmental loads, together with the large set of possible environmental conditions experienced during the turbine lifetime, results in special challenges for the estimation of both ultimate and fatigue loads. It is typically assumed that the environment can be described by a stationary stochastic process on short timescales, i.e., within 10 minutes. Since the sea state typically develops on a longer timescale and can be assumed to be stationary for durations of up to 3-6 hours (Barltrop and Adams, 1991), this is based on the observation of a spectral gap for the wind speed (Van der Hoven, 1957), but for offshore wind conditions, this assumption is not without critics (Heggem et al., 1998). The long-term distribution of environmental loads is strongly site-dependent and needs to be evaluated from long-term measurements or simulations involving climate models.

The analysis of loads on wind turbine structures has been strongly regulated (e.g., IEC, 2009; DNV, 2013) and currently consists of running many thousands of 10-min load cases that sample the possible loads experienced by the turbine during the projected lifetime, using dedicated wind turbine simulation software (Vorpahl et al., 2013). Some of these 10-min load cases are transient cases (e.g., emergency shutdown or turbine start-up) or with simplified, regular environmental loads, but the major part consists of simulating the normal operation ("power production") of the turbine in an irregular environment. These analyses are based on a numerical model of the wind turbine that is (1) as realistic as possible, and (2) subject to a realization of the stochastic processes characterizing the environmental loads. Therefore, in addition to the many different environmental conditions that need to be assessed, it is necessary that each load case is repeated a number of times in order to obtain a sufficiently accurate estimate of, e.g., the fatigue damage experienced by the turbine in this situation; as an example, the current DNV rules prescribe using a minimum of six different random realizations of the wind field and sea state (DNV, 2013).

The complexity of a wind turbine and its physical environment renders structural design and optimization of the turbine a multidisciplinary design optimization problem (Collette and Siarry, 2003; Martins and Lambe, 2013). Unfortunately, the system is *tightly coupled*, i.e., optimizing individual parts of the turbine separately will, in general, lead to suboptimal or even potentially infeasible solutions. As an example, in the beginning of the offshore deployment of wind turbines, it was attempted to separate the effects of wind and waves on turbines, but it has been shown that this leads to unacceptably large errors in the fatigue damage estimates (Kühn, 2001).

Probably the most important example of such an interaction effect is the issue of *aerodynamic damping* (Salzmann and Van der Tempel, 2005). When the wind turbine moves into the wind (tower motion in the along-wind direction), the relative wind velocity experienced by the blades is changed, and the aerodynamic force in the opposite direction increases. Vice versa, moving out of the wind results in a decrease of the force in that direction. This results in an apparent additional damping force that reduces horizontal motions of the wind turbine. The aerodynamic force signals are thereby explicitly dependent on the motions of the turbine, and this means an accurate structural analysis of a wind turbine has to be coupled with an aerodynamic rotor simulation, in order to take tower motions into account. Various attempts have been made to replace the rotor simulation by a force or displacement time series acting at the tower top, but the additional aerodynamic damping then has to be realized in one way or the other, in order to obtain accurate results. This issue has not been resolved satisfactorily for general, turbulent wind conditions (Salzmann and Van der Tempel, 2005; Van der Tempel, 2006).

Cost Models for Wind Turbines

Another complication that affects the relevance of structural optimization for wind turbine structures is the fact that, ultimately, it is the life cycle or levelized *cost of energy* that needs to be minimized, not the weight of the wind turbine. This is, in general, subject to many unknowns (e.g., fluctuations in market commodity prices and competition with other industries). Even when focusing on the capital cost of the wind turbine, one needs to consider costs related to manufacturing. Comparisons or cost estimates that do not take into account the additional expenses for welding joints, for example, are unrealistic. The Hungarian school of structural optimization has extensively considered *cost models* for manufacturing of steel structures (Farkas and Jármai, 1997, 2013), but it is at present unclear to what degree these earlier cost models can be used for wind turbines. Common cost models used for offshore wind turbines are typically based on empirical data (Fingersh et al., 2006; Jamieson, 2011; Kaiser and Snyder, 2012) and are too coarse-grained for use with engineering optimization as envisaged here.

Optimization of Towers for Small Wind Turbines

Towers for onshore wind turbines have been the subject of many studies. For small wind turbines (e.g., <50 kW), basically three different concepts have been explored (Wood, 2011): (1) the monopole tower, often with polygonal sections and slip-joint or bolted connections; (2) the lattice tower; and (3) the guyed tower. The last is often the cheapest solution, but the design and analysis of the connectors for its tendons is typically involved, requiring detailed finite element (FE) analysis that is not readily automated.

Load calculations for small wind turbines follow a simplified load model (Wood, 2011), which defines static mean and maximum loads, as well as maximum peak-to-peak load ranges. The analysis of towers for small turbines, using only static loads, can be done semi-analytically. Even in this simple case, with only a few design parameters that characterize the top and bottom diameters, as well as the wall thicknesses of the individual sections, the problem is nontrivial: "The base diameter, d_h, and the section thicknesses were chosen iteratively to keep the capacity factors to 0.6 or less. It is important to note that there is no obvious procedure for doing this, so an optimization method would be valuable, especially if it included a measure of cost in the objective function" (Wood, 2011). The optimization in this example was therefore performed with a genetic algorithm, using static thrust forces and moments at the tower top.

Optimization of Wind Turbine Structures Using Static Analysis

Static analysis is still common for large wind turbines, also, as far as design optimization is concerned. Bazeos et al. (2002) describe a detailed tower design for a 450-kW turbine, using a single static load case. Improving the analysis, Lavassas et al. (2003) used 18 different static load cases, indexed by wind speed and defined by the wind turbine manufacturer, to validate their tower design for a 1.0-MW machine. The same method and loads were used by Uys et al. (2007) to optimize the tower with respect to diameters and the number of stiffeners for a 1.3-MW wind turbine. The optimum design was achieved for the minimum number of stiffeners, resulting in savings of a few percent in cost. The cost model included manufacturing costs, using baseline values of 1 USD/min of work and 1 USD/kg of steel used. Using the data for a commercial 1.0-MW Acciona turbine and its tower, Chantharasenawong et al. (2011) achieved a reduction of more than 20 percent in tower weight by increasing diameters and reducing section thicknesses, thereby reducing the capacity factor for buckling failure (but still within allowable limits).

The studies mentioned so far considered circular monopile towers. A few authors worked with lattice towers; e.g., Gencturk et al. (2012) optimized the parameters of a transmission line lattice tower for a 100-kW wind turbine. Using the Tabu search heuristic, a reduction of more than 20 percent in weight could be achieved, using a small set of static load cases (including both turbine and seismic loads). Long et al. (2012) describe design and optimization of a lattice tower for ULS (extreme) loads in a 5-MW offshore wind turbine. Static analysis and buckling checks were performed, in order to determine the optimal bottom leg distance.

Perelmuter and Yurchenko (2013) describe optimization of a circular tower but with a more refined analysis that uses dynamic sensitivity factors and takes into account the fluctuations in loads caused by turbulence. Their optimum tower for a 5-MW onshore turbine is 140 m high and has a mass of 340 tons, which is roughly the same weight as for the 87.6 m tower of the NREL 5-MW offshore wind turbine model (Jonkman et al., 2009). Also, Torcinaro et al. (2010) use static analysis for extreme loads that is complemented by buckling and modal analysis, the latter to avoid issues with structural frequencies and the 1P/3P excitations from the rotor. Their design of a 5/6-MW offshore wind turbine on a tripod converged in less than 40 iterations.

Optimization of Wind Turbine Structures Using Frequency Domain Analysis

Frequency domain analysis is common in offshore engineering, and a number of studies have considered it for wind turbines. The general approach is described in detail by Van der Tempel (2006). Recently, Thiry et al. (2011) discussed monopile design and optimization with a genetic algorithm, using a semi-analytical wind turbine model, for which transfer functions were calculated and convoluted with the power spectral densities of the wind, assuming a rigid rotor and no aerodynamic damping. Long and Moe (2012) have studied the design of lattice towers in the frequency domain, using the Dirlik (1985) method to estimate fatigue damage, thereby identifying optimal bottom leg distances. Aerodynamic damping was implemented as a linear dashpot element. Although the approach is not valid in the presence of nonlinearities and the fatigue calculation is only approximate, the main advantage of frequency domain analysis is its performance. In fact, several thousand load cases can be checked in a few minutes, which makes it the tool of choice for preliminary design.

Optimization of Wind Turbine Structures Using Time-Domain Analysis

The most accurate analysis method for wind turbines is time-domain simulation. This is the method prescribed by standards for certification analysis (IEC, 2009; DNV, 2013). It has been realized during the European Opti-OWECS study that, in order to improve the cost efficiency of wind turbines, their design has to be integrated. This means that all components of a wind turbine need to be designed jointly and, also, that installation, operation and maintenance should be considered in the design process (Kühn, 1999, 2001). A first example of a study using tailored dynamics is the work of Yoshida (2006), who used an integrated analysis tool to assess the structural integrity of the tower design by time-domain simulations and optimized it with a genetic algorithm.

The main disadvantage of such an approach, with current simulation ratios of less than real-time, is that it is extremely time-consuming. Especially for more complex support structures, such as jackets or lattice towers, the number of load cases that can be used is normally strongly limited. The work of Zwick et al. (2012) only considers a single load case, for example. Interestingly, it demonstrates *weak coupling* between individual members in a lattice tower; each member can be optimized individually, assuming that (1) the loads are not changed when changing the member's geometry, and (2) the loads are not changed when changing the geometry of other members. These *locality assumptions* are only approximately true, and the members are therefore only resized to within 10 percent of optimality, but this approximation is sufficiently accurate, such that the optimized design will still adhere to the design limits, while exhibiting less weight. Only 20-30 iterations are needed until the method converges, which makes it possible to optimize and compare optimal turbine configurations for different site conditions (Muskulus et al., 2013).

While this study shows that even complex support structures can, in principle, be optimized quite efficiently, there is still scope for additional improvements of the design. Using a stochastic search algorithm, Molde et al. (2014) showed that even larger reductions in structural weight could be achieved than with the simple iteration scheme based on these locality assumptions.

The same method was used by Chew et al. (2013) to investigate optimal design of a 3-legged jacket support structure. Comparison with a similar 4-legged version showed that the 3-legged structure can, in principle, be more cost-efficient. Not only is the design using slightly less weight, but the manufacturing costs will be significantly less due to the decreased number of welded joints. King et al. (2013) focused mainly on joint design. Starting from a reference design with cast nodes, it was shown by integrated analysis that all cast joints could be replaced by forged elements when using some form of load mitigation control. Assuming 40,000 GBP per cast node and 5,500 GBP per ton of forged steel, this alone resulted in a cost saving of 12 percent.

SPECIAL ISSUES FOR THE OPTIMIZATION OF WIND TURBINES

Simplified Wind Turbine Models for Analysis and Design Optimization

Considering the need for wind turbine analysis under a large number of load cases, a possibility to speed up the analysis is the use of simplified or reduced-order models of wind turbines. This is an active area of research. One of the first examples is the study by Negm and Maalawi (2000) on the tower design for a 100-kW wind turbine. The authors developed a simplified turbine model based on a cantilevered beam and used it to assess five different objectives for optimization: to minimize the weight, maximize the stiffness, maximize the stiffness/mass ratio, to optimize the eigenfrequencies, or to maximize the structural eigenfrequencies (using a weighted average of the first three eigenfrequencies). Interestingly, the best results were achieved by the simple strategy of maximizing the eigenfrequencies of the tower. A general way to obtain a reduced-order model and a single beam description of a wind turbine support structure is described by Murtagh et al. (2004).

Although developed for a floating wind turbine, the model of Sandner et al. (2012) demonstrates that, by using only a few degrees of freedom and careful programming (e.g., precomputing and storing often needed values in lookup-tables), a factor of 100 can be gained in computational speed, while preserving most of the accuracy (for normal power production load cases).

System-Level Optimization of Wind Turbines

Optimization of wind turbines, in general, has a long history, and for completeness we mention the most relevant and recent developments, even though many of these do not consider the design of support structures. Typical for the earlier methods, Collecutt and Flay (1996) discussed how to optimize rated power as a key design parameter for a specific site, using energy production cost and an empirical cost model. Fuglsang and Madsen (1999) developed the first multi-disciplinary framework for gradient-based rotor optimization, including detailed time-domain simulations of rotor dynamics, but without considering the support structure and foundation. Fuglsang and Thomsen (2001) extended the method and stressed the importance of not only optimizing the annual energy production (via the aerodynamic design of the blades) but also optimizing the loads (structural design of the blades). A cost reduction of around 10 percent against a reference offshore turbine design could be achieved, mainly by increasing the rotor diameter and reducing the hub height. At that time, this demonstrated that site-specific turbine design is feasible. In a more comprehensive study (Fuglsang et al., 2002), an improved cost model was developed, and a largely reduced set of load cases (also reducing the length of the time series) was used. The results indicate that, although the best cost reduction was achieved by redesigning the entire turbine, by focusing only on *redesign of blades and tower*, a major cost reduction, of more than 6 percent in their case, already could be achieved.

One issue with integrated design and optimization of wind turbines is the large number of parameters and the complexity of working with many different engineering disciplines, often using different assumptions and model fidelities. The general framework of multidisciplinary design optimization (Alexandrov and Hussaini, 1997; Martins and Lambe, 2013) has been developed to cope with this situation. Often, a multi-level approach is used, in which specific parts or aspects of the turbine are optimized separately on lower levels, and a global, high-level optimizer integrates and jointly optimizes the complete system. Maki et al. (2012) have demonstrated this approach for rotor design, using a kriging metamodel for the global optimization. Ashuri (2012), using a limited number of model parameters, has performed an automatic optimization process of the complete wind turbine that also includes the tower design. The jacket-sizing tool developed by Damiani and Song (2013) has been implemented in a general, modular framework that allows for using different optimization algorithms and also includes, for example, automatic code-check capabilities.

The latest trend in wind turbine design is to increase the fidelity of the aerodynamic design, e.g., by performing computational fluid dynamics simulations as part of the design process. In contrast to the normally used blade element momentum theory calculations, this would allow more accurate assessment of turbine behavior under nonstandard conditions, e.g., with significant yaw error. In order to make optimization with such expensive analysis methods feasible, multi-level and automatic model reduction approaches are needed (Petrini et al., 2010; Bottasso et al., 2012). Metamodels or the Taguchi method have also been tested successfully for aerodynamic design (Hu and Rao, 2011).

As becomes apparent, very few studies consider tower, support structure, foundation design and optimization with an integrated simulation model. Ashuri (2012) is almost the single exception and shows that the cost of energy can be significantly reduced when using such an integrated approach towards optimization, which often involves tradeoffs between rotor and support structure design. As an example application, a 5-MW wind turbine was optimized for a North Sea site, resulting in a more expensive support structure and turbine but with a larger annual energy production. The cost of energy was thereby decreased by 2-3 percent. Lozano-Minguez et al. (2011) discuss a framework for evaluating and comparing support structure concepts but without consideration of design or optimization aspects.

A general overview of wind turbine optimization, also including wind park layout problems, is also available (Baños et al., 2011). Réthoré et al (2013) present a comprehensive system-level optimization of a complete wind park.

Optimization of Floating Wind Turbines

Floating wind turbines constitute a class of concepts that become economically interesting for medium-to-deep water depths. Their design and optimization pose significant additional challenges (Butterfield et al., 2007). The seminal paper by Clauss and Birk (1996) on the optimization of floating offshore structures is still relevant here, but floating wind turbines are smaller and more dynamic than structures used in the oil and gas industry. Brommundt et al. (2012) showed the importance of turbulent fluctuations in the wind field for a semisubmersible floater, which translated and contributed a major part to the fluctuations of mooring-line loads.

A well-known optimization tool, currently exclusively for use with spar-type floating turbines, is Windopt (Fylling and Berthelsen, 2011). It minimizes the total weight of the turbine and allows for designing the spar buoy, the mooring system and the power cable, using sequential quadratic programming and a combination of commercial analysis tools. A limitation of Windopt is that the wind turbine rotor is represented only as a state-dependent drag coefficient, i.e., a state-dependent force acting in a single node at the top of the tower. A more realistic model was used by Myhr and Nygaard (2012), who optimized the structural design of a tension-leg buoy wind turbine, using two extreme load cases as assumed design drivers in a fully-integrated time-domain wind turbine simulation.

Geotechnical Aspects

Uncertainty about soil conditions is a major challenge for the design and optimization of wind turbines. In fact, this problem is often ignored in the literature. Obviously, the foundation does significantly influence the dynamic characteristics of the turbine (e.g., Zaaijer, 2006; Muskulus, 2011), but variability in soil conditions has not been sufficiently addressed for the design process. Horgan (2013) compares four different wind turbine foundation types in terms of their economic potential but only considers extreme, static loads when performing the geotechnical design. Byrne and Houlsby (2003) discuss alternatives to piled foundations. Soil damping has been addressed by Versteijlen et al. (2011) and Damgaard et al. (2013); the latter contains an overview of the literature and further references.

DISCUSSION

Simulation Technology

The limitations inherent in current simulation technology pose a major challenge for the optimization of wind turbine structures. In order to obtain accurate results, not only are simulations computationally expensive, but there do not exist many numerical codes that are able to simulate a complete wind turbine. The existing codes might not be well suited for automatic optimization, being essentially developed for human designers and interactive use, and less for batch processing and automatic interfacing with optimization algorithms. Experience has shown that the development of an efficient workflow is often the most time-consuming task. As an example, Gutierrez et al. (2013) discuss what is involved for the well-known FAST turbine simulation code.

Simplified wind turbine models (e.g., Sandner et al., 2012) provide an excellent solution for preliminary design but should ideally be integrated into a common tool that allows for selecting the desired model fidelity. Parts of this idea have been realized with the Engineer Design Data approach developed by Strach et al. (2012). Alternative techniques, such as frequency-domain analysis or impulse-based substructuring, can potentially speed up the analysis significantly (Van der Valk and Rixen, 2012).

Related Topics

Optimization of structures is a wide field, and there are a couple of additional topics relevant for wind turbines that we want to briefly mention here. Obviously, not only the sizing of support structures, but also the optimization of their topology could be automated, i.e., the optimal placement of joints and elements under dynamic loads and with eigenfrequency constraints (Bendsøe and Sigmund, 2003). These problems are much harder than simple sizing optimization, especially if, in addition, discrete pipe diameters and thicknesses (e.g., Achtziger and Stolpe, 2007) or performance constraints are considered (Liang, 2004).

Probabilistic design and reliability issues have been mentioned before; Sørensen and Tarp-Johansen (2005) discuss these specifically for wind turbines, reporting optimal reliability levels for different failure modes and presenting reliability-based inspection models.

Load mitigation is an important topic in itself; it is possible to reduce the design-limiting loads on turbine towers and support structures by both passive or active dampers (Colwell and Basu, 2009; Lackner and Rotea, 2011) and by implementing advanced control strategies, e.g., combined with LIDAR monitoring of the wind field that allows predicting environmental loads before they hit the turbine (Bossanyi et al., 2012; Schlipf et al., 2013).

RECOMMENDATIONS

The field of structural optimization is large, but the literature on optimization of wind turbine structures is rather limited. We want to summarize this review with a number of recommendations for both future work and present practices:

(1) Gradient-based optimization. In order to quickly find optimal design solutions, especially for large design spaces, it is important to use gradient-based methods. In practice, the estimation of gradients can be problematic, e.g., in a simulation-based approach because of the need for dynamic, time-domain analysis. The recommendation is to use analytical gradients as much as possible, e.g., utilizing the adjoint method with static load cases (for design against extreme loads) or adapting modern techniques of calculating gradients for time-dependent problems (Choi and Kim, 2005a, 2005b; Kennedy and Martins, 2013).

(2) Models with a hierarchy of fidelities. For designers and researchers alike, it is important that numerical models with the right fidelity, i.e., level of detail, can be selected for a given analysis problem. Ideally, there should be possibilities for automatic transformations from one level of detail to another (a well-known example is the automatic reduction of detailed blade structural models to equivalent beam models for use with load simulations). This would make it possible to use low-fidelity models for early design phases and use more accurate models during later stages. Model reduction in structural dynamics is extensively discussed by Qu (2010).

(3) Decoupling of rotor dynamics. For the analysis of the support structure dynamics, it is desirable to be able to replace the rotor in the numerical model by a simplified, computationally more efficient representation. Ideally, this would only be a force/momentum time series acting on the tower top and a single damper element to represent the aerodynamic damping. It is recommended to develop simple rotor models that provide more accuracy than this essentially uncoupled model, while still allowing the use of general structural analysis software. It is currently not clear whether the necessary accuracy can be achieved by such a strategy, but the possibility of optimizing a subset of decoupled systems would be advantageous in a multi-level optimization approach.

(4) Demonstration of cost reduction potential. So far, a convincing demonstration of the potential for cost reduction with automatic wind turbine design and optimization methods is lacking. The difficulty here is to define conditions for a *fair comparison* and to design a structure that fulfills the requirements of certification analysis, while still being cheaper than a human-designed baseline design.

(5) Reducing uncertainty of simulations. This is desirable on general principle, since uncertainty translates into safety margins, i.e., potential for optimization that cannot be utilized. As an example of current interest, more accurate modeling of joints can lead to lower, more realistic estimates of fatigue damage (Dubois et al., 2013).

(6) Best practice for design of wind turbine structures. Although some guidelines or recommendations for wind turbine design are scattered in the literature, an accepted best practice that takes a new designer (or researcher) step-by-step through the process of designing a wind turbine tower or support structure is missing.

(7) Explore probabilistic design. Although intrinsically more difficult and time-consuming, reliability-based design allows for a clearer, better defined optimization problem. An interesting question is whether probability evolution algorithms (Li and Chen, 2009) can potentially be more efficient than time-domain analysis in assessing wind turbine designs. One should ask oneself if the current paradigm of simulating a wind turbine "as realistically as possible" is the correct approach – for such a strongly driven system, would it not be possible to use specially crafted input signals that test the wind turbine response to wind and wave forcing in a more efficient way? Can we somehow get the accuracy of time-domain simulation with the speed of frequency-domain analysis?

(8) Reduction of load cases. There is still no clear verdict on what the dimensioning and design-driving load cases for the tower and the different support structure concepts are. When performing computer-aided optimization of wind turbine structures, currently only a few load cases can be considered (Fuglsang et al., 2002; Myhr and Nygaard, 2012). This issue becomes even more relevant for floating wind turbines, which exhibit a significant increase in load cases that have to be considered, compared to bottom-fixed turbines (Robertson and Jonkman, 2011).

(9) Interfaces for efficient, integrated design. An issue of practical importance is the development of efficient, standardized interfaces and methodologies that allow different groups or companies, working on the design of different components of the turbine, to perform consistent load simulations. A well-known case is the interface between wind turbine manufacturer and support structure designer (Seidel, 2010). Simplified numerical models of the support structure have been developed for this purpose, e.g., the so-called sequential approach (Seidel et al., 2005), but do not always accurately represent the dynamics of jacket support structures (Zwick et al., 2014). A different motivation for common interfaces is the possibility of using existing or in-house software in one company with models from another company or designer, i.e., the ability to keep the same workflow and tools when working together with parties using different tools. The so-called Functional Mockup Interface (Blochwitz et al., 2012) has been established as a relevant standard that is being used, e.g., by the automotive industry. With respect to design optimization, the OpenMDAO project provides an integrated framework (Coroneos and Pai, 2012). Integrated design of a wind turbine tower and foundation has been considered by Haghi et al. (2014), demonstrating the feasibility and potential of this approach.

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