Robust Requirements and Design Optimization for Offshore Wind Turbines Utilizing Approximate Model Technology


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This paper describes a framework for robust and reliability-based design optimization of offshore wind turbine support structures, which is an important topic. Current design practice of wind turbines is based on deterministic design, as specified in the relevant international design codes, where the influence of uncertainties about loads and resistances is approximated by safety factors. This approach has a number of well-known limitations. Assumptions about uncertainties have been made during calibration of the safety factors but cannot be expected to accurately mirror the relevant uncertainties for each design, especially with regard to changes in technology such as the continuing growth in the size and rating of the turbines that lead to new dynamic phenomena. This can result in overtly conservative designs, while at the same time it does not guarantee the desired structural reliability (Muskulus and Schafti, 2015).

Probabilistic design offers methods that allow these issues to be addressed in a natural, flexible, and accurate way. Traditionally, two main variants can be distinguished: Reliability-based design optimization (RBDO) aims at optimizing the design, ideally using its lifetime cost, while at the same time guaranteeing a probability of failure below a defined threshold, which is typically considered to be $10^{-6}$ (Sørensen, 2008). Alternatively, robust design optimization (RDO) aims at optimizing a weighted sum of a design’s expected performance (again, in terms of cost) and the variance of this performance. The uncertainty about the structural analysis is an explicit goal of the optimization and thereby reduced as well. However, RDO does not guarantee a specific probability of failure per se. In its original formulation by Doltsinis and Kang (2004), the reliability of the design enters through a constraint on the expected maximum structural performance, parameterized by a feasibility index $\beta$. This method still uses the traditional safety factor format of deterministic design. The constraints take the form where the mean structural response (e.g., mean bending stresses) plus $\beta$ times the standard deviation fulfill the limit state equations; in other words, an expected characteristic maximal response is used in the design checks.

The paper by Yang and Zhu (2015) proposes a hybrid approach in which the uncertainty about the design is minimized through the RDO approach, while the constraints are replaced by probabilistic constraints bounding the exceedance of the limit state, i.e., the probability of structural failure, at some threshold.

Probabilistic structural analysis of wind turbines is a complex, challenging task, due to the large number of costly design evaluations needed. The major strength of the paper is that it shows how some of these difficulties can be overcome by using meta-modeling techniques, in this case a surrogate model for the structural response to extreme loads by way of kriging. In addition, the authors use global sensitivity analysis (Saltelli et al., 2008) to identify the most influential parameters for the structural response. These parameters are the ones that need to be controlled and optimized. It is encouraging to see these powerful techniques of modern structural optimization applied to the design of offshore wind turbines, and I hope that the readers of the Journal of Wind and Ocean Energy will find inspiration and motivation from the paper to familiarize themselves with these useful techniques.

That said, the paper has a number of shortcomings that the reader should be aware of. Even using statistical meta-modeling techniques to decrease the computational burden, the design problem had to be simplified significantly. Although it is true that the ultimate limit state is typically the critical one in early design, it is far from satisfactory that the authors did not consider fatigue damage. The analysis has been performed with decoupled wind loads, which seems reasonable in this situation. This approach will not work, however, for structural analysis in operational conditions where the important interaction between support structure motion and aerodynamic loads, specifically the so-called aerodynamic damping, cannot be resolved. This will lead to a vast overestimation of structural response if not addressed (Muskulus, 2015).

Some of the assumptions made about the uncertainties and the design goals are rather questionable as well. It is not understandable to me how the diameter of the structural elements can have a COV of 0.03, for example. For a structural element with a diameter of 2 m, this means a manufacturing tolerance of ±6 cm (standard deviation), which seems excessive. Also, the required probability of exceeding the limit state equations was taken to be 0.02, which seems unacceptably high, compared to the normal requirement of $10^{-6}$. Unfortunately, many interesting or even important details about the method used are not explained in the paper; e.g., it is unclear what the limit state equations are exactly, so it cannot be judged how severe these issues are. The reader is also left to make educated guesses with respect to the sensitivity measure used.

In conclusion, the paper has some severe shortcomings with regard to presentation and some of the assumptions made, but it shows that probabilistic structural design of wind turbine structures is feasible and a promising avenue of research. Interest in this topic will almost surely increase in the future.

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AUTHOR'S REPLY

Michael Muskuls presents valuable comments on our paper (Yang and Zhu, 2015). Our main task at the start of the study was to put forward a feasible framework of robust design optimization (RDO) for the supporting structure of an offshore wind turbine. This feasible framework includes two aspects: Robust design requirements (comparing with deterministic design and reliability-based design optimization) and approximate models (comparing with FE models).

The metamodel technique is used successfully in aeronautical design, and choosing the ideal type of metamodel to maintain accuracy is also a very critical problem. For one optimization problem, we know the input parameters design space, and then we can calculate the output response. The metamodel technique can describe the black-boxed system according to the input and output information. From another viewpoint, this is the original system that includes input and output information. This is a solution space constructed for the original system. Then by design of experiment (DOE), we can give design parameters for the system. Finally, according to these samples, we can construct an approximation model that describes the relationship between input and output information. The RDO can be based on the approximation model instead of FE simulation.

Offshore wind energy is about to break out this year in the Chinese market. Many enterprises are shifting to using integrated analysis software, such as Bladed, to calculate the response of the overall unit. Independent design that calculates the aerodynamic loads and structural dynamic loads separately is withdrawing from the historical arena. The traditional independent design cannot take the interactions between the aerodynamics and structural dynamics into consideration. Meanwhile, fatigue load is one of the essential elements for the load safety evaluation of the wind turbine. There are a lot of load cases relative to fatigue analysis, as defined in international guidelines and specifications (e.g., GL 2010 (2010), IEC 61400-1 (2005)). An entire simulation of the wind turbine will need at least 1,000 load cases based on different wind and wave directions, yaw angles, wind speeds, and their combinations. We believe that such simulations of the structural responses of offshore wind turbines can be solved in a real project by applying the metamodel technique. Fatigue is a critical problem for offshore structures. In order to maintain structure safety, it is better to have optimization considering fatigue (Yang et al., 2011). Fatigue reliability-based design optimization by metamodel was successfully applied for an umbilical/flexible riser bending stiffener (Yang and Wang, 2012). The main purpose for this work is to demonstrate that the robust design optimization (RDO) strategy can be applied for the offshore wind turbine design process. If we want to apply the proposed methodology to a real project, we should consider more detailed information.

We did not explain much about the comparison with the approximate model due to journal page limitations. A more detailed and interested analysis is presented in another paper (Yang et al., 2015). As we know, finite element method is time-consuming for considering uncertainties. As for the sensitivity measure used in this article, first, we select all the parameters of the supporting structure, defining the initial values and the lower and upper bounds of these parameters, as listed in Table 1. Then we use the Optimal Latin Hypercube (OLH) method (Stocki, 2005) to calculate the contributions of these parameters to the dynamic responses. The OLH method is a widely used method of DOE (Saltelli et al., 2008), since it can significantly reduce the number of selected sampling points to save computational cost without losing representative and uniform requirements. The contribution represents the sensitivity of parameters, which can be seen in Fig. 1. The more sensitive one parameter is, the higher value of contribution one parameter will get. Parameters with the least contributions will be deleted from the design variables to save the optimization cost. Judging by the plot, four parameters are considered to be the main design variables for optimization. They are $T_1$, $T_2$, $T_5$, and $D_2$.

In this work, the metamodel technique is used to construct response surface approximations for the RDO of offshore wind turbine design. The smooth nature of the response surface approximations eliminates numerical noise, which is inherent to the numerical analysis procedures used to estimate the output responses. The present research proposes the application of metamodel to the RDO analysis. Accurate response surfaces will be developed that may be used instead of numerical analysis procedures. A major advantage of developing approximate models for RDO is that they may lead to rapid and feasible analysis methodology. This metamodel strategy will be an interesting research topic for Journal of Ocean and Wind Energy readers. The methodology developed and presented here provides a road map for future applications of offshore structures.

REFERENCES


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