Simulation-based structural reliability of support structures

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Introduction

With the current focus on cost reduction, the design of turbines has to be improved. As part of this challenge we consider the support structure here. Structural optimization is the art of reducing its cost without increasing the risk of failure beyond an acceptable level. This is difficult to achieve with deterministic design, especially when a number of important factors are uncertain. In other words, optimal support structures can only be achieved with probabilistic design where their structural reliability is checked.

Approach

We determine structural reliability of support structures using the standard approach [1,2] where failure occurs when load effects (e.g. fatigue damage and ultimate loads) are larger than structural resistances (e.g. yield strength and fatigue resistance). The uncertainty in the resistances is described by probability distributions. The load effects are determined by load simulations. Uncertainties in the environmental loads and in the structural model can be included (e.g. soil stiffness) [3,4,5]. The load effects are then determined by Monte Carlo sampling of these uncertain parameters and performing standard load simulations with each of these, slightly different, models. Due to the large number of analyses it is important to use an efficient method. In our approach we have decoupled the rotor and support structure. Aerodynamic loads are included in the support structure model as time series in all six degrees of freedom at tower top. In addition, a linear viscous damper represents the aerodynamic damping. The uncertainty in the value of this damping constant has been included as a parameter.

Main body

Decoupling the rotor and support structure dynamics leads to an efficient method. The support structure model is linear elastic and we only use the tangent stiffness of the soil (based on the p-y approach), so the numerical model is completely linear. Using a previously developed approach [6,7] we can calculate the response time series for a 60 minute load case in a few seconds (per location of interest) using a general purpose graphics processing unit (GPU). For this we first determine impulse-response functions by applying small impulse loads to the structural model in all six degrees of freedom where aerodynamic loads act. We then use the Duhamel integral to calculate the response to an arbitrary load time series by convolution of the impulse-response with the load time series. This can be efficiently performed in parallel on the GPU. The response to wave loads is similarly calculated and simply superposed, again using the linearity of the numerical model. The resulting response time series are used to perform code checks following an offshore standard [8] and to determine fatigue damage from rainflow counting and the Palmgren-Miner linear damage accumulation rule. Performing these analyses for a large number of Monte Carlo samples (using a simple form of importance sampling to improve the convergence) allows for determining the probability of failure. We have implemented and tested the approach with two different support structures, a monopile and a jacket structure. In contrast to previous work [9] we have extended the method and it now 1) uses a load case table with operational and extreme conditions, including turbine standstill, 2) uses realistic and comprehensive code checks based on an existing offshore standard, 3) uses more realistic wave loads. Examples show the effect of uncertainty in soil conditions, manufacturing uncertainty, and aerodynamic damping (Figure below).

Conclusion

We have demonstrated that structural reliability of support structures can be assessed quite efficiently, when using a simplified rotor load model. This allows for reliability-based optimization of support structures and probabilistic design under relatively realistic conditions. Moreover, uncertainties in factors influencing the response can be naturally taken into account. The examples show that this can be quite important.

Learning objectives

Delegates will learn about structural reliability and how this can be determined for support structures. They will see what is probably the fastest load simulations in the world and will realize the possibilities that such speed of analysis enables. Finally, they should understand why probabilistic design is important.

References

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Figures

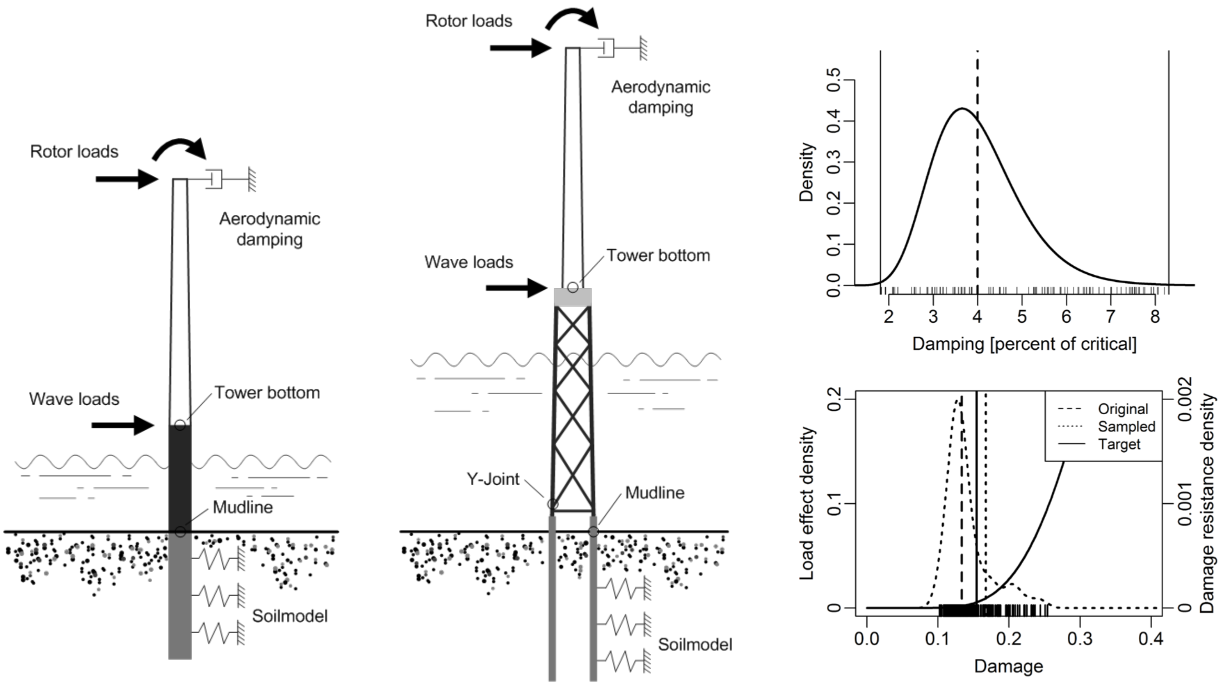

Figure 1. Illustration of the approach, including an example result.

a) Numerical model of the monopile support structure. b) Numerical model of the jacket support structure. c) Probability density function of the assumed aerodynamic damping. The mean (4%) is marked by the broken line. Random samples using a uniform sampling distribution are shown at the bottom. d) Importance of uncertainty in system parameters. The design achieves a target probability of less than 10^{-4} (broken and solid line). If the uncertainty in aerodynamic damping is taken into account, however, the probability of failure exceed this level slightly (dotted line).