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On Assessing the Accuracy of Offshore Wind Turbine Reliability-based Design Loads from the Environmental Contour Method

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We discuss the use of the environmental contour method to derive design loads for an active stall-regulated offshore wind turbine. Two different Danish offshore environments, Rødsand and Horns Rev, are considered for the locations of the turbine. The accuracy of the derived design loads is assessed by comparing them with exact solutions derived using full integration over an accurate description of the failure domain. The error in estimating design loads is introduced because 2 key assumptions of the method are violated: first, the limit state surface, especially in the operating range of the turbine, is not well-approximated by a tangent hyperplane at the design point; and second, failure in any of the possible turbine states (e.g., operating or parked states are discussed here) needs to be considered in computing accurate failure probabilities. It is recommended that environmental contours and iso-response curves be plotted and interpreted before establishing design load levels.

INTRODUCTION

Inverse reliability techniques are commonly used when there is interest in establishing design levels associated with a specified reliability of probability of failure. The heuristically appealing Inverse First-Order Reliability Method (Inverse FORM), also called the environmental contour method, is an example of an inverse reliability technique that has been applied to estimate design loads in many applications, including offshore platforms (Winterstein et al., 1993) and onshore wind turbines (Fitzwater et al., 2003; Saranyasoontorn and Manuel, 2004). For offshore wind turbine applications, Christensen and Arnbjerg-Nielsen (2000) utilized the environmental contour method to derive design levels for shear and overturning moment at the seabed for an active stall-regulated wind turbine located at 2 different Danish offshore sites. Even though application of the environmental contour approach to deriving design loads for wind turbine structures has been well established (see, for example, Saranyasoontorn and Manuel, 2004), it has not been clearly explained how the treatment of multiple turbine states (or accounting for the possibility of failure under different conditions, such as *operating* or *parked*) typical for wind turbine applications can affect the accuracy of the derived design loads. Errors in deriving design loads may be introduced if certain assumptions inherent in the environmental contour method are violated. Two of the most important assumptions of the method are as follows:

- that the failure probability is associated with a single governing failure mode (or turbine state) alone, and any probability of failure associated with other states is neglected in the calculations;
- that a local linearized limit state surface can serve as an approximation of the true limit state surface by virtue of using a tangent hyperplane at the *design point*, and that the desired (target) probability of failure or reliability may be associated with the tangent hyperplane.

We shall see that errors may be large in practical situations when the true limit state surface is highly nonlinear, or when it has no well-defined shape that can be reasonably approximated by a tangent hyperplane, and/or when failure in secondary turbine states can become reasonably likely compared to primary turbine states. Both of these sources of error are common when considering wind turbines where failure might result, for example, under either operating or parked conditions (turbine states). In this paper's illustrations using offshore wind turbines, the different regimes associated with the machine's power production require us to consider the possibility of failure in either operating or parked states. Additionally, as we shall see, the transition from operating to parked conditions, which takes place abruptly at the machine's cut-out wind speed, introduces highly irregularly-shaped failure surfaces to which a single tangent hyperplane would be a poor approximation. We also discuss how, in some situations, due to the error sources mentioned above, design loads based on the environmental contour method can be wrongly interpreted, ascribing more importance to derived environmental conditions of one state than is found when the design load is computed using exact full integration approaches.

The objective of this study is to investigate the various error-related issues more closely in order to make recommendations regarding the use of environmental contour methods to derive design loads for onshore and offshore wind turbines. For the sake of illustration, we consider an offshore wind turbine located at 2 different sites. The characterization of the random wind and wave environment and dependence on loads is of interest here. We will study failure due to extreme shear or overturning moment at the base of the offshore wind turbine. For these extreme/ultimate limit states, failure in either of 2 states is considered: When the turbine is operating and the corresponding hub-height wind speed is between the cut-in and cut-out wind speeds, or when the turbine is parked, and the wind speed is higher than the cut-out wind speed. Although the turbine and environmental conditions used in this study are the same as those analyzed and described at great length in the previous study by Christensen and Arnbjerg-Nielsen (2000), our goals in the present study are very different. Our focus is not on simply deriving design loads. Rather, we will attempt to explain and interpret results by highlighting the role of each turbine state as it influences the derived design load for a specified return period. We also compare the predicted design

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