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Reliability-Based Design Optimization of Wind Turbine Blades for Fatigue Life under Wind Load Uncertainty

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Abstract

Conventional wind turbine blades have been designed using fatigue life predictions based on a fixed wind load distribution that does not fully capture uncertainty of the wind load. This could result in early fatigue failure of blades and eventually increase the maintenance cost of wind turbines. To produce reliable as well as economical wind turbine blades, this paper studies reliability-based design optimization (RBDO) of a wind turbine blade using a novel wind load uncertainty model. In the wind load uncertainty model, annual wind load variation has been extended over a large spatiotemporal range using 249 groups of wind data. The probability of fatigue failure during 20-year service life is estimated using the uncertainty model in the RBDO process and is reduced to meet a desired target probability of failure. Meanwhile, the cost of composite materials used in the blade is minimized by optimizing the composite laminate thicknesses of the blade. In order to obtain the RBDO optimum design efficiently, deterministic design optimization (DDO) of a 5-MW wind turbine blade is first carried out using the mean wind load obtained from the uncertainty model. At the DDO optimum design, fatigue hotspots for RBDO are identified among the laminate section points. For efficient sampling-based RBDO process to handle dynamic wind load uncertainty, instead of generating surrogate models of the overall output performance measure, which is 20-year fatigue life, a number of surrogate models of the 10-minute fatigue damages D10 at the hotspots are accurately created using the dynamic Kriging (DKG) method. Using these surrogate models and the wind load uncertainty model, probability of failure of 20-year fatigue life at these hotspots and their design sensitivities are calculated at given design points. Using the sampling-based method, RBDO of the 5-MW wind turbine blade is carried out starting at the DDO optimum design to meet the target probability of failure of 2.275%.