There is a large drive to reduce the cost of energy of wind energy generators. Various tracks are being considered such as enhanced O&M strategies through condition monitoring, increased manufacturing efficiency through higher production volumes and increased automation, improved resource assessment through turbine-mounted real-time site assessment technologies, improved components reliability by increased laboratory testing, increased number of prototype test turbines before serial production, larger rotor and tower concepts for both onshore and offshore installations, advanced drive train designs, advanced load alleviation control systems, extensive industrialization and modularization of components, cost-out programs, increased components redundancies where possible, etc [Schwabe, P., Lensink, S., Hand, 2011]. Twenty five years ago an offshore wind turbine consisted of 2/3 of the total capital cost (excluding foundations), today this value has dropped down to roughly 30 40% [IRENA, 2012, CleanEnergyPipeline, 2014]. Wind turbine manufacturers and researchers have indeed delivered on the promise of cost reduction, but the question remains: can we do more?

The research in this thesis aimed to contribute to the larger objective of reducing cost of energy through the implementation and application of uncertainty quantification and probabilistic methodologies on specific areas of design of wind turbines, namely: (a) aerofoil aerodynamic lift and drag, (b) load alleviation control features and (3) fusion of output from multi-fidelity aero-servo-elastic simulators. Why uncertainty quantification and probabilistic methodologies? Because such methodologies provide tools that makes it possible to design a wind turbine to a specific probability of failure, which means wind turbines are as strong as necessary, but no stronger [Veldkamp, 2006].

The original contributions of this research were:

- A comprehensive list of sources of uncertainties affecting the prediction of extreme loads on a wind turbine. Such a list is indeed subjective and subject to scrutiny and updating depending on a researcher's, scientist's and engineer's background, know-how and experiences.
- A fully encompassing stochastic model of aerofoil aerodynamic lift and drag coefficients, followed by a quantification of the effect of aerodynamic uncertainties on the extreme loads and an optimization of the partial safety factors.
- An in-depth analysis of how advanced load alleviation control features such as cyclic pitch, individual pitch, static thrust limiter, condition based thrust limiter and an active tower vibration damper affect the structural reliability of a multi-megawatt wind turbine blade and tower when the extreme turbulence model is uncertain. The novelty is in the subsequent cost and reliability based optimization of the load partial safety factor, turbine geometry, controller failure rate and structural reliability metrics of a large multi-megawatt wind turbine equipped with advanced load alleviation control features. The objective here was to investigate how the load partial safety factors are affected by the performance of various configurations of advanced load alleviation control features to limit the excursion of extreme loads above a certain threshold.
- A review, implementation and demonstration of 5 analytical methods for fusing output from multi-fidelity aero-servo-elastic simulators with application to extreme loads on a wind turbine. Analysts and designers increasingly use multiple commercial and research-based aero-servo-elastic simulators such as FLEX, FAST, BLADED, HAWC2, Cp-Lambda, etc. to compare the predicted coupled dynamic loads and response of the system. This review attempts to demonstrate the potential to fuse (combine) the output of various multi-fidelity aero-servo-elastic simulators to predict the most likely response and the corresponding model uncertainty.
- A detailed implementation of a model fusion technique called co-Kriging to predict the extreme response in the presence of non-stationary noise in the output (i.e. the magnitude of noise varies as a function of the input variables) in the case when the low and high-fidelity aero-servo-elastic simulators of the same wind turbine are implemented by two independent engineers (i.e. human error and uncertainty in the modelling and input assumptions are implicitly included). We demonstrate the co-Kriging methodology to fuse the extreme blade root flapwise bending moment of a large multi-megawatt wind turbine by using two aero-servo-elastic simulators, FAST [Jonkman and Buhl, 2005] and BLADED [[Bossanyi, 2003b], [Bossanyi, 2003a]].

The main findings of the work and their implications were:

- The assessment of uncertainties in the aerodynamic lift and drag were done through a heuristic based stochastic model which replicates the uncertainties in airfoil characteristics by parameterizing the lift and drag coefficients polar curves. In the IEC61400-1 design standard for wind turbines, a value of 10% for the coefficient of variation (COV) on the uncertainty related to the assessment of the aerodynamic lift and drag coefficients is used. The findings in this research indicate that while this value is appropriate for certain structural components such as blade tip flapwise and main shaft tilt and yaw moments, it is conservative for components such as blade root flapwise, edgewise and tower. An overall assessment of uncertainties in the aerodynamic static lift and drag coefficients showed (a) a tangible reduction in the load partial safety factor for a blade and (b) generally a larger impact on extreme loads during power production compared to stand-still. Therefore, the way forward is for wind turbine manufacturers to further update the stochastic model by integrating their own data to assess the impact of the aerodynamic uncertainty on their specific wind turbine. The stochastic model can also be used as a tool for a probabilistic design and risk mitigation in the early stages of the aerodynamic design of a wind turbine rotor.
- Large uncertainties in the extreme turbulence model can be significantly mitigated through the use of advanced load control features. The magnitude, scatter and shape of the annual maximum distribution of the loads is dependent on the performance of the load alleviation control features such as individual pitch control and condition based thrust limiter to limit the excursion of extreme loads above a certain threshold. The reduction in the mean of the annual maximum load distribution and the coefficient of variation due to the action of advanced load alleviation control features in turn translated into a higher structural reliability level in the face of uncertainties in the extreme turbulence model.
- The probabilistic cost and reliability based optimization methodology showed that a tangible reduction in the load partial safety factors can be achieved when advanced load alleviation control features are used while maximizing the benefits.
versus costs and while maintaining acceptable target probability of failure. However, some configurations of advanced load alleviation control features yield annual maximum load distribution with very low coefficient of variation (i.e. on the order of 2.3%); in this case the model and statistical sources of uncertainties dominate the reliability analysis resulting in higher load partial safety factors. It was shown that the benefits were maximized when the annual failure rate of advanced load alleviation control features is around 10^{-3}. A key finding is that the overall probability of failure of the structure-control system is by far dominated by the annual failure rate of the control system. This means that decreasing the annual failure rate of the control system would have a larger impact than improving the reliability of the structure.

- Assuming that the output of the high-fidelity (BLADED) and low-fidelity (FAST) aeroservo-elastic simulators follow similar trends as a function of an independent variables (i.e. bending moment as a function of wind speed), the co-Kriging based methodology fused the "noisy" extreme flapwise bending moment at the blade root of a large wind turbine from a low fidelity and a high-fidelity aero-servo-elastic simulators; the co-Kriging predictions compared well with validation data. Therefore, the way forward is to fuse output from multiple aero-servo-elastic simulators in order to reduce model uncertainties and refine the probability of failure of the wind turbine structure.

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