Summary of IEA Topical Expert Meeting on Structural Reliability of Wind Turbines

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Structural reliability is presently an area in wind turbine design that draws attention from many different interest groups. Manufactures are looking for reliable methods to design larger and more optimised wind turbines in a safe way. Research institutes and universities are currently involved in activities aiming at developing and refining basic tools within the field. Standardisation bodies, such as IEC, are putting great emphasis on developing rules and regulations in the area.

As a result of this common interest, the symposium attracted 15 participants from universities, research institutes, classification bodies and industry giving 11 presentations covering different aspects of the theme of the symposium. Each of the presentations is briefly summarised below:


In the design of wind turbine structures, ultimate loading as well as fatigue loading is addressed. The design process involves aeroelastic modelling of the wind turbine as well as specification of appropriate load scenarios. In addition to uncertainties associated with load and resistance, both the structural modelling, the aerodynamic modelling and the load modelling may be encumbered with uncertainty. These uncertainties all have an impact on the safety against structural failure. Traditionally the involved uncertainties can be categorised into different disjoint classes:

Natural variability. This is uncertainty associated with a random character inherent in the physics of a system. Related to wind turbine design, straight forward examples are stochastic wind loading caused by turbulence, stochastic wave loading and variability in material resistance. Natural variability is a type of uncertainty, which cannot be reduced.

Model uncertainty. This class of uncertainties relates to the choice of deterministic as well as stochastic models applied in the design computations. Generally speaking, the model uncertainty is caused by insufficient knowledge/ability or selected simplifications in the mathematical formulation of the physical system. The model specification is a crucial step that might be responsible for a substantial amount of uncertainty – for example the well known “tail sensitivity” of reliability computations. Model uncertainty can be reduced by using a better model.

Statistical uncertainty. Statistical uncertainty is closely associated with a limited amount of available data. It manifests itself as uncertainties in the relevant parameter estimates.
Statistical uncertainty can be reduced by increasing the amount of data, e.g., by further sampling.

Structural reliability analysis constitutes the synthesis of the above listed sources of uncertainty into a measure of the probability of survival for the structure, and such analyses can further be condensed into structural design codes by so called partial safety factor calibration.

**Gunner C. Larsen and Anders M. Hansen (Riso): Uncertainty in Design Loads.**

There is an obvious interest in quantifying the magnitude of uncertainty associated with design loads as established based on traditional aeroelastic computations. The present presentation deals with this topic.

Based on a number of simplifying assumptions, an analysis of the uncertainty on the design fatigue loading, of a modern active stall regulated 2 MW wind turbine (in normal operation), have been conducted. Model uncertainty is neglected, and only the statistical uncertainty and the natural variability, on four vital input parameters (i.e. design turbulence intensity, aerodynamic lift- and drag parameters and the intercept in a S-N curve fatigue formulation), are taken into account in the analysis. The analysis has been performed for both an onshore- and an offshore siting situation. In both cases, load specifications from the IEC 61400-1 code have been adopted.

The following conclusions emerge from the analysis:

- Uncertainty in the material (fatigue) properties is a dominating factor. However, as it is caused (mainly) by natural variability it can not be substantially reduced unless different materials are introduced;

- Uncertainty in predicted lifetime, caused by uncertainty in the design turbulence intensity as well as in lift- and drag coefficients, is also significant - these can be reduced by increasing the number of observations/predictions and improving the methods for predicting the aerodynamics coefficients;

- The resulting uncertainty is not additive in the selected four uncertainty factors.


The atmospheric turbulence has a major effect on the fatigue design of wind turbine structures. Of the parameters characterising the atmospheric turbulence, the turbulence intensity is the most important in this respect. The uncertainty associated with this quantity is therefore of interest in relation to reliability assessment of wind turbine designs.

The present work presents a model that quantify the statistical uncertainty on the design turbulence intensity in terms of a probability density function. The model is based on the conventional formulation of the design turbulence intensity (i.e. a sum of the mean turbulence intensity and a factor times the standard deviation on the turbulence intensity). The model relies on a simplifying assumption on the "parent" distribution type, and it is
expressed on closed form, with the number of independent statistical degrees of freedom as the only parameter. Using the model, it has been demonstrated, that the uncertainty on the design turbulence intensity tend to decrease with increasing mean wind speeds, and tend to decrease with increasing sample size (as expected).

Luc Rademakers and Henk Braam (ECN): Structural Reliability and Design Methods.

The use of structural reliability methods is fairly new within wind turbine design, but an increasing interest for this technical discipline has been recognised in the field. The present work describes the past and present Dutch activities in the area.

The introduction of structural reliability methods in the wind turbine industry requires both that the methods are further developed and made available for manufactures, and that the design codes are adjusted to also include this design philosophy (f.x. specification of target values for reliability). To support development structural reliability methods in the field, ECN has in the past been involved in two Joule III projects. The Prodeto project aimed at a calibration of partial safety factors for blade fatigue loading as well as for blade ultimate loading, whereas the Profar project dealt with the scatter in blade fatigue properties. It emerged from these projects that it is very complicated to develop complete probabilistic design methods for blade manufactures, among others, due to a number of complex failure mechanisms (fatigue, failure of the bonding line, buckling, failure of the spar, etc.) in connection with complex material behaviour of composite materials. For the support structure of offshore sited wind turbines, the introduction of probabilistic methods is more straight forward, because the offshore industry already have experience in utilising these methods and because of more simple material behaviour. As the need at the same time is believed to be higher, the Dutch efforts on the field are presently devoted to offshore support structures.


Currently an effort is made in the area of extrapolation of normal operational load effects to lifetime extremes. The interest in this area is motivated by the fact that extrapolated load effects are in current design comparable to, or even larger than, standstill loads. The work presented regarded a numerical study of the extreme loads in a wind farm in which the presence of neighbouring turbines increase the ambient turbulence level and induces wakes with especially high turbulence. It has been shown that in a rectangular grid configuration where the spacing in the one direction is somewhat smaller than in the other direction, it suffices to consider only the loads induced be the wakes in the first direction. The work was based on Sten Frandsen’s formulas for wake effects, assuming essentially that characterising the increased turbulence by an increase in turbulence intensity solely is sufficient, and extrapolation of Gumbel distributions fitted to simulated 10.-min-extremes. Others have instead considered the peak distributions to which they have fitted quadratic Weibull distributions. Taking statistical uncertainty into
consideration it is disputable what approach is the better. The numerical study included the consideration of more mean wind speeds. It turned out that a few mean wind speed bins around the bin with the highest 10.-min. extreme response gives the main contribution to the extrapolated lifetime extreme.

Niels Jacob Tarp-Johansen, Peter Hauge Madsen & Sten Frandsen (Riso): Introduction to Debate on Reliability Level of Wind Turbines.

In connection to the revision of the IEC standard 61400-1: Wind Turbine Generator Systems - Part 1: Safety Requirements, 2nd Ed. a simplified probabilistic safety factor calibration is carried out. Present safety factors have been adopted from existing structural design codes ranging over many different types of structures and a wider set of load cases than relevant to wind turbine engineering. What is offered is a wind turbine specific calibration leading to safety factors optimal for wind load dominated structures. The following issues have been dealt with:

- extreme loads and extreme loads during operation (i.e. currently not fatigue loads)
- reliability level
- differentiation of safety factors with respect to load model uncertainties
- statistical simulation uncertainties, and
- weighting of safety factors with respect to the ratio of aerodynamic loads to gravity loads in a given cross-section.

Of central importance in the work is the choice of model uncertainties. The choice of uncertainty model for shape factors was discussed. It showed that there are differences between interpretations of shape factor uncertainties in structural engineering and wind turbine engineering.


The main parts of the Danish structural code system (Basis of design, Action and Loads, Concrete, Steel, Timber, Masonry and Foundation) have been revised in the period 1996-1999. The paper describes the main steps in the probabilistic code calibration performed in order to obtain the optimized partial safety factors in these new Danish Structural Codes (1999). First, the reliability level is evaluated for a number of typical, simple structures designed according to the previous Danish Structural Codes (1982) with a stochastic model for the uncertain action and structural variables relevant for Danish conditions. The reliability analyses show a non-uniform reliability level for different materials and actions. Next, new partial safety factors in a slightly modified code format are calibrated such that the average reliability level is the same in the new codes as in the previous codes, i.e. the average reliability level in the previous structural codes is used as
the target reliability level. Using the optimized partial safety factors, a more uniform reliability level is obtained for different types of materials / structures and for different types of actions.

The reliability level is discussed in relation to a severe storm in December 1999 in Denmark, where wind speeds slightly larger than the level of the characteristic value were measured. The observed structural damages and the lack of damages on structures designed in accordance with the Danish structural codes are used as basis for a discussion of the target reliability level to which the partial safety factors were calibrated. Combinations of variable actions are not part of the calibrations carried out.

The code format and partial safety factors in the Danish structural code are compared to those in ‘Basis of Structural Design’, Eurocodes (2001). Compared to the Danish code, the Eurocodes give a much more non-uniform distributed safety level as function of material type and loading type. Finally the main structure in the new Eurocode for wind actions was presented.

**Peter Hauge Madsen (Riso): IEC Standardisation.**

IEC is an international organisation dealing with standardisation within all fields of electrotechnology. The IEC’s standards are vital since they represent the core of the World Trade Organization’s Agreement on Technical Barriers to Trade (TBT). The standardisation work in IEC is organised in a number of Technical Committee’s (TC’s), each representing a specific electrotechnical field.

The present contribution deals with the ongoing standardisation efforts in TC88 covering the field of Wind Turbine Systems. To draft documents for new standards, TC88 sets up a project team, while for modifying standards, it sets up a maintenance team. Each are composed of a limited number of experts appointed by the members of the committee. Presently, a maintenance team - MT14 - is working on a general revision of standard IEC 61400-1 WTGS – Part1: Safety Requirements, 2nd edition. In particular, MT14 shall consider the limitations in the present standard in relation to installations offshore, in wind farms and/or in complex terrain. Having completed its task the MT14 team will be disbanded, and the prepared documents will be submitted to the National Committees for voting with a view to their approval as international standards. IEC’s international standards are reached by international consensus among the National Committees.

**Knut O. Ronold (Det Norske Veritas): Statistical analysis of simultaneous wave and wind climate data**

As an introduction, a brief presentation was given of DNV’s recent activities with respect to probabilistic analysis of wind turbines. Subsequently, emphasis was given to presenting results from statistical analysis of simultaneous wave and wind climate data. The basis for the analysis consists of simultaneous wave and wind data obtained at two Danish offshore locations in 1999 and 2000. The following climate variables were considered:

- Significant wave height
• Zero-upcrossing period for waves
• 10-minute mean wind speed
• standard deviation of wind speed

The statistical analysis was used as a basis for stochastic modelling – in terms of probability distributions – of these wave and wind climate variables as needed in probabilistic analysis of wind turbines. A scheme was presented by which one of the variables is modelled as an independent variable and each of the other variables is modelled as a dependent variable whose distribution parameters are functions of the independent variable and/or one of the other dependent variables. Generic distribution models suitable for representation of the distributions were identified and distribution parameters were estimated by fitting to the data.


For a modern pitch controlled turbine, the ultimate flap-wise deflection is often controlling the design of the blade structural flap-wise stiffness. This is due to requirements related to the blade/tower clearance. The work presented deals with estimation of this parameter.

Traditionally, a Type-1 Gumbel distribution has been fitted to such extreme deflections as obtained from numerous aeroelastic simulations of an identified "most critical" mean wind speed situation. However, the computations indicate that the ultimate deflection may have an asymptotic upper limit. Two different phenomena could, dependently or independently, be responsible for this phenomenon. Firstly, there might exist an upper limit for the maximum lift obtainable for the blade, due to an assumption that amplitudes of wind gusts, with rise times faster than the pitch response, will be physical limited in size in a standard roughness driven boundary layer. Secondly, the deflection process is conditioned on two, to some extent independent, processes - the pitch process and the wind gust process. The observed asymptotic upper limit in turn make the Type-1 Gumbel fit deviate in the upper tail. This misfit can be circumvented by replacing the Type-1 Gumbel with an extreme-value distribution type III.


Extreme loading of wind turbines have obtained increasing attention in resent years. The work presented considers the statistical uncertainties related to extreme response distributions. The extreme responses in question are the flap moment at the blade root and the overturning moment of the support structure of an offshore wind turbine situated in the North sea. The statistical uncertainties treated here are the uncertainties concerning the choice of distribution and uncertainties concerning the distribution parameters. The uncertainties are treated with Bayesian analysis. The inclusion of the uncertainties has only marginal effect for the long-term estimates of the extreme responses when non informative priors for the distribution parameters are used. The inclusion of uncertainties may have larger effect for real measurement data.
Discussion

At the finalising discussion at the meeting there was a common interest to proceed with information exchange in this area in the future. An Ad Hoc group was sent up in order to formulate a proposal for an annex dealing with structural reliability. The following persons volunteered to participate in the group. Dick Veldkamp, Luc Rademakers, Gunner Larsen, Peter Hauge Madsen, Niels Jacob Tarp-Johansen, John Dalsgaard Soerensen and hopefully someone from NREL.

The following issues was identified as important for further consideration:

1. External conditions (parameter estimation etc.)
2. Partial safety factor calibration
3. Application of partial safety factors in dynamic simulation
4. Extrapolation of loads
5. Assessment of relevant uncertainties
6. Stochastic modelling of uncertainties
7. Limit states (fatigue, ultimate)
8. Material strength models
9. Target reliability level
10. Case studies and comparisons with good examples
11. Code format (which partial safety factors etc.)
12. Onshore and offshore

Deliverables:

1. Recommended Practice
   - code format
   - partial safety factors
   - methods for adjustment of safety factors
2. Annual workshops

Proposed title: Structural safety of Wind Turbines

Time frame: 2 - (3) years

The intention was to be able to present a proposal for a new Annex at the next Executive Committee meeting in Germany April 2002. This implies that the proposal must be ready for distribution to the ExCo secretary mid March.