ANALYSIS CONCERNING WIND LOADS EFFECT FOR FATIGUE OF TALL TOWER

COBREA CODRIN RUDOLF
BIBIRE LUMINITA

University of Bacau

Abstract: The paper presents a methodology for using measured or simulated loads to produce a long term fatigue-load spectrum at specified environmental conditions and at desired confidence levels using statistics based on the regression of the statistical moments over the input conditions, the uncertainty (due to the limited data set) in the long-term load distribution is represented by 95% confidence bounds on predicted loads.

Keywords: tall tower, wind, load, effect, fatigue

1. INTRODUCTION

The empirical approach uses only the measured or simulated data without any fitting of distributions or extrapolation to higher values that would be seen if more data were obtained. One of the disadvantages of using a purely empirical approach is, therefore, that the loading distribution may not be representative. Perhaps a subtler shortcoming is that the uncertainty in the loads is almost impossible to characterize.

With regard to uncertainties in loads and how they might be dealt with in design, one might expect that these uncertainties could be covered by the use of standard specifications of characteristic loads (derived from a specified high turbulence level) and safety factors.

However, current standard load definitions use safety factors that do not depend on the relative uncertainty in the load estimates. Either the margins are larger than they need to be when load estimates are reasonably well established (i.e., exhibit low uncertainty), or they fail to cover the uncertainty when load estimates are based on limited data (i.e., large uncertainty cases).

Parametric load distribution models offer significant advantages over empirical models; they provide a means to (1) extrapolate to higher, less frequent load levels, (2) map the response to the input conditions, and (3) calculate load uncertainty.

For example, Ronold have published a complete analysis of the uncertainty in a wind turbine blade fatigue life calculation. He used a parametric definition of the fatigue loads, matching the first three moments of the wind turbine cyclic loading distribution to a quadratic (transformed by a squaring operation) Weibull distribution.

2. I.E.C. REQUIREMENTS

Because Wind Turbine Generator is very dangerous, a special commission, named International Electrotechnical Commission (I.E.C.) settles these aspects.

The increase in probability, over the deterministic results in order to achieve 95% confidence, is found to be relatively modest. This reflects the benefit of having as many as 101 10-minute samples. If the same mean trends had resulted from fewer samples, the resulting 95% confidence results would be correspondingly higher than the mean results.

Note also that, at least for flap-wise loads, the conservatism induced by the IEC turbulence models exceeds that required to cover our statistical loads uncertainty, based on the data at hand. Of course, as noted earlier, this IEC conservatism may be desirable to cover other sources of uncertainty. Finally, we caution again that these long-term load results are intended for example purposes only; accurate numerical values would require data across a broader range of wind speeds.

The loads specified by IEC 61400-1 Wind Turbine Generator Safety Requirements [1] for design must be defined for a specified combination of mean wind speed and turbulence intensity known as the Normal Turbulence Model[5]. The standard provides an equation for the standard deviation of the ten-minute wind speed, σ_1, that depends on the hub-height wind speed and two parameters, I_{15} and a.

$$\sigma_1 = I_{15}(15m/s + aV_{hub}/(a+1) \qquad (1)$$

Equation 1 is based on wind speed standard deviation data gathered from around the world and aggregated into a common data set. The equation was created to be "broadly representative of sites with reasonable international marketing interest," and does not represent any single site. *S* is intended to represent a *characteristic value* of wind-speed standard deviation. Certification guidelines are provided for high (A) and moderate (B) turbulence sites. I_{15} defines the characteristic value of the turbulence intensity at an average wind speed of 15 m/s, and *a* is a slope parameter when *s* is plotted versus hub-height wind speed. The values of these parameters for each category are shown in Table 1.

Table 1: Parameters for IEC turbulence categories.

CATEGORY	A (HIGH)	B (MODERATE)
I_{15}	0.18	0.16
a	2	3

The Category B moderate turbulence specification is intended to roughly envelope (i.e., be higher than) the mean plus one sigma level of turbulence for all the collected data above 15 m/s. Similarly, Category A envelopes all collected values of turbulence intensity for mean wind speeds above 15 m/s and is above the overall mean plus two sigma level in high winds. Clearly, the IEC Normal Turbulence Model is intended to be conservative for all but the most turbulent sites.

It is a relatively straightforward matter to create a loading distribution that meets the standard criteria when using an aeroelastic simulation code. Input winds can be generated for any combination of wind speed and turbulence intensity. Representative loadings can, in theory, be generated by simulating repeatedly until sufficient data are produced to drive the uncertainty to an arbitrarily small level. Practically, however, it would be beneficial to generate a loading distribution with small, or at least known, uncertainty from a smaller data set. This is where the parametric approach provides significant value. By means of regression of load statistics (e.g., moments) over the entire range of wind speeds and turbulence levels, the uncertainty in the values of the parameters defining the short-term distributions at any specified turbulence condition can be estimated.

In the case of measured loads, it may be simply impossible to gather data at the specified turbulence conditions because of the limitations of the test site. In that case, the parametric approach provides a method to interpolate to a specified turbulence level using all of the data collected (thus adding to the confidence of the interpolation), or to extrapolate beyond the limits of the measurements. In either case, the parametric approach simplifies the generation of fatigue loads to Standard specifications.

It is critical that the load distributions generated by any statistical methodology be adaptable for use in existing design standards. Moreover, it is arguably even more important that the load model provide insight into how the design standards might be improved in future revisions.

The standards should require an accurate reflection of the load distribution with sufficient conservatism to cover the uncertainties caused by the limited duration of the sample, whether based on simulation or field measurements. Only then can design margins be trimmed to the point of least cost while still maintaining sufficient margins to keep reliability levels high.

The approach to load modeling is not uniform across the wind community by any measure. This lack of commonality in approach was reflected in the working group that produced IEC's Mechanical Load Measurement Technical Specification [2]. No consensus could be obtained on how to use measured loads to either create or substantiate a fatigue load spectrum at the conditions specified in the Safety Standard [1]. All that is offered are several examples of differing approaches in an annex of the specifications [2].

Fatigue load spectra are generated for arbitrary site conditions (wind speed and turbulence intensity distributions) by using parametric models to fit the short term load spectrum to the first three moments of the truncated rainflow range distributions and regressing the moments over wind speed and turbulence intensity.

The spectra are generated to specified IEC conditions for wind speed Class and turbulence Category. The spectra are also generated for as measured scatter in the turbulence levels across all wind speeds. The comparison of the two approaches reveals the level of conservatism that results from assumed high turbulence levels written into the current standards.

The selected confidence level can be calculated using the statistics from regression analysis. Since the confidence interval depends on the uncertainty in the load characterization, it could provide a better margin of safety on the loads than can be accomplished with an inflated turbulence level. The parametric approach presented here illustrates how statistically based standards may be able to reflect the uncertainty in the loading definition caused by finite length data records.

3. CONCLUSIONS

International standards for wind turbine certification depend on finding long-term fatigue load distributions that are conservative with respect to the state of knowledge for a given system. Statistical models of loads for fatigue application are described and demonstrated using flap and edge blade-bending data from a commercial turbine in complex terrain. Distributions of rainflow-counted range data for each ten-minute segment are characterized by parameters related to their first three statistical moments (mean, coefficient of variation, and skewness).

The procedure based on these three moments is shown to match the measured load distributions if the non-damaging low-amplitude ranges are first eliminated.

The moments are mapped to the wind conditions with a two-dimensional regression over ten-minute average wind speed and turbulence intensity. With this mapping, the short-term distribution of ranges is known for any combination of average wind speed and turbulence intensity. The long term distribution of ranges is determined by integrating over the annual distribution of input conditions. First, we study long-term loads derived by integration over wind speed distribution alone, using standard-specified turbulence levels.

Next, we perform this integration over both wind speed and turbulence distribution for the example site. Results are compared between standard-driven and site-driven load estimates.

Design constraints for wind turbine structures fall into either extreme load or fatigue categories. In the case of extreme load design drivers, the load estimation problem is limited to finding a single maximum load level against which to assess the structural strength.

For design against fatigue, however, loads must be defined over all input conditions and then summed over the distribution of input conditions weighted by the relative frequency of occurrence. While this might seem to be a more daunting task, it is in many ways quite similar to the extreme load problem, as can be seen by comparing with Fitzwater and Winterstein[1].

In both cases, the loads must be determined as functions of wind speed (or other climatic conditions). Parametric models define the response, statistically, with respect to input conditions. Such models fit analytical distribution functions to the measured or simulated data. The parameters of these distribution functions can be useful in defining the response/loads as a function of the input conditions. The end result, then, is a full statistical definition of the loads over all input conditions.

In the most prevalent alternative to parametric modeling, an empirical distribution of loads (i.e., a histogram describing frequency of occurrence of the modeled response quantity) is used to define the turbine response at the conditions of the measurement or simulation.

When using simulations, a ten-minute time series is generated at specified environmental conditions using an aeroelastic analysis code. The time series is rainflow-counted and the number of ranges in specified intervals is summarized in histograms. The histograms serve as empirical distributions that are taken to be representative of the response of the turbine at those particular conditions.

The full lifetime distribution is then obtained by summing the distributions after weighting by the frequency of occurrence of the wind speed associated with each simulated data segment included in a histogram interval.

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