Fatigue Life Variability and Reliability Analysis of a Wind Turbine Blade*

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Abstract

Wind turbines must withstand harsh environments that induce many stress cycles into their components. A numerical analysis package is used to illustrate the sobering variability in predicted fatigue life with relatively small changes in inputs. The variability of the input parameters is modeled to obtain estimates of the fatigue reliability of the turbine blades.

Introduction

The large rotating machines that convert wind energy into electricity are called wind turbines. The harsh environments that accompany the most energetic wind sites include substantial amounts of turbulence that drive the dynamics of the structures, resulting in cyclic stresses and fatigue damage. The blades, which must withstand the dynamic loads, account for a significant portion of the total cost. The ability to design blades that have acceptable levels of reliability is a driving force in the cost of energy and the success of the technology.

Fatigue analysis tools are now available for combining the relatively complicated interaction of random vibration, varying wind speed, and material fatigue properties. Parametric studies, shown below, indicate the extreme sensitivity to input parameters that are, at best, uncertain. The usefulness of a fatigue analysis tool is suspect when the designer realizes the magnitude of this sensitivity. It is therefore of interest to build a reliability based formulation that provides a probabilistic measure of meeting a target lifetime for economic decision-making purposes.

Deterministic Fatigue Model

The stress state imposed upon a turbine component includes a functional relationship to the velocity of the wind impinging on the turbine. If the annual wind speed distribution is described by a probability density function, p(V), the service lifetime of a turbine component may be estimated by the relation:

$$D(\Delta t) = \int_{V_{ci}}^{V_{co}} p(V) \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{n(S_m, S_a, V, \Delta t)}{N(S_m, S_a)} \, dS_m \, dS_a \, dV \qquad . \quad (1)$$

This relation is based on Miner's Rule for damage accumulation, where S_m is the mean stress, S_a is the alternating stress, $N(\cdot)$ is the total number of cycles required to fail the materials at the stress state (S_m, S_a) and $n(\cdot)$ is the number of stress cycles at stress state (S_m, S_a) imposed on the turbine blade in time Δt by a wind of velocity V.

V_{ci} and V_{co} are the cut-in and cut-out wind speeds, respectively. When the damage, D, equals one, the component is expected to fail. As this formulation is linear, the service lifetime, T_f, of the component is given by $T_f = [1 / D(\Delta t)]$.

The solution to Equation 1 can be approached using analytical and/or numerical techniques. In the case of the former, a set of restrictive assumptions can be used to obtain a closed form solution. In the case of the latter, Equation 1 is discretized and solved numerically. Here, we will describe first numerical and then analytical approaches to the estimation of the service lifetime of a turbine component.

Numerical Fatigue Analysis Code

The LIFE2 code [Sutherland, 1989] is a specialized numerical solution of Equation 1. The code guides the user through the steps necessary to define all the inputs while setting up data bases of the wind resource, constitutive properties of the turbine material, stress state in which the turbine operates and operational parameters for the turbine system. It then solves Equation 1 for the average damage rate and estimates time to failure.

Closed Form Analytical Solution

It is possible to get a closed form solution to Equation 1 if a few restrictive assumptions are applied [Veers, 1990]. These restrictions include: a two parameter Weibull distribution for wind speed; a Rayleigh distribution for stress ranges at a given wind speed; a linear increase in stress RMS with increasing wind speed; a constant mean stress; and a simple power law S-n curve. Damage is assumed to accumulate at all wind speeds (i.e., the turbine is never shut down). Substituting these distributions and relationships into Equation 1, solving the integral, and defining failure when damage equals one yields (with symbols defined in Table I)

$$T_f = \left\{ C f_o \left[\frac{\sqrt{2}\, M\, K\, V_m}{(1 - S_m / S_u)(1/\alpha_v)!} \right]^b \left[\frac{b}{2}\right]! \left[\frac{b}{\alpha_v}\right]! \right\}^{-1} \quad . \quad (2)$$

The above restrictions may be inappropriate when there is sufficient data to show otherwise, but are generally applicable in the early design stages before sufficient testing has been done to provide more customized input.

TABLE I. Definition of Variables in the Closed Form Solution.

Symbol	Definition	Mean	COV	Distribution
C	S-n Coefficient	5×10^{21}	0.613	Weibull
f_o	Avg. Frequency	2.0 Hz	0.2	Normal
M	RMS Slope	0.45 MPa/(m/s)	0.05	Normal
K	Stress Con. Factor	3.5	0.10	Normal
S_m	Mean Stress	25 MPa	0.20	Normal
V_m	Mean Wind Speed	6.3 m/s	0.05	Normal
α_v	Dist. Shape	2.0	0.10	Normal
b	S-n Exponent	7.3	-	Constant
S_u	Ultimate Strength	285 MPa	-	Constant

Test Bed Example: Parameter Studies

Sandia National Laboratories has erected a research oriented, 34-meter diameter, Darrieus, vertical axis wind turbine (VAWT), near Bushland, Texas. The highest stressed region of the blade has been analyzed using the LIFE2 code [Ashwill, et al., 1990]. Several parameters are varied, including the characterization of the site's wind regime, the S-n curve for the extruded aluminum blades, and estimates of the blade stress. The influence of these parameters on the estimated service lifetime is illustrated using three wind speed distributions, see Figure 1: a Rayleigh distribution with a 6.2 m/s (14 mph) average; the Amarillo Airport (located 20 miles across flat terrain from Bushland) distribution with a 6.6 m/s (15 mph) average; and the Bushland site distribution with a 5.8 m/s (13 mph) average.

Table II lists the estimated fatigue lives using both the analytically predicted (Ana) and measured (Mea) operating stresses for each of the three wind regimes. In the analytical case a published "reference" (Ref) S-n curve is used. A least squares curve fit (LSC) to newly generated S-n data is used for the measured case. Predicted lifetimes vary by a factor of 50, depending on the input parameters.

Table II. Effect of the wind Regime on Lifetime (in years)

Wnd	Fat	OPS	Life
R	Ref	Ana	11.9
A	Ref	Ana	7.86
B	Ref	Ana	29.4
R	LSC	Mea	150.
A	LSC	Mea	100.
B	LSC	Mea	391.

Reliability Estimate

The closed form solution of Equation 1 has been used as the failure state function in a FORM/ SORM reliability analysis using the software developed by Rackwitz [1985]. Relatively low levels of uncertainty were assumed to fit the situation where substantial test data has already been obtained. The distributions for the random variables are shown in Table I. The resulting median lifetime is 370 years. However, the estimated probability of less than a 20 year target lifetime is about 2% (1.8% with FORM and 2.2% using SORM with reliability indices of 2.1 and 2.0). Importance factors are also calculated, see Figure 2. The high variability of the S-n data dominates the uncertainty, while the stress concentration factor and wind speed distribution shape make up the bulk of the remainder.

Figure 1. Typical Wind Speed Distribution

A Log-Normal Formulation: Closed Form Solution

The closed form solution in Equation 1 is well suited to approximate analysis using log-normal techniques [Wirsching, 1984]. If the mean stress, ultimate stress and wind speed distribution shape are assumed to be constants, the equation is purely multiplicative in the remaining random variables. When the distribution of all the random variables is log-normal, the reliability index with a target lifetime of T_t is given by
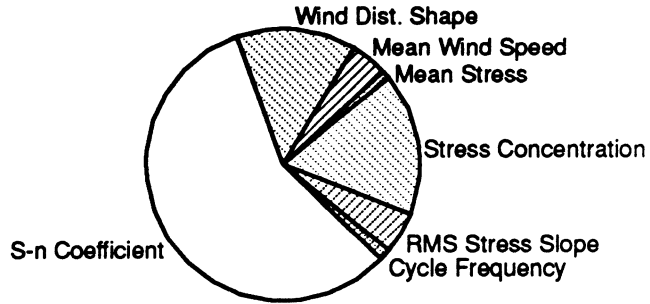

Figure 2. Importance Factors

$$\text{Reliability Index} = \frac{\ln(T_f / T_t)}{\ln[\prod_i (1 + C_i^2)^{b_i^2}]^{1/2}} \quad , \quad (3)$$

where C_i is the coefficient of variation, COV, of the ith random variable.

The FORM/SORM estimates are analytically checked. Using the means and COVs in Table I, both FORM and SORM produce an index of 2.7 (0.3% probability of failure), while Equation 3 yields an index of 2.9 (0.2%). The change in the distribution of the S-n coefficient from Weibull to log-normal, with identical mean and COV, is largely responsible for a ten-fold decrease in probability of failure.

Summary

The calculation of fatigue lifetimes of wind turbine blades is accomplished with a sophisticated numerical analysis package (LIFE2), which indicates the sobering variability in predictions with relatively small changes in inputs. A fatigue reliability calculation shows that even with a median lifetime of hundreds of years, the probability of premature failure is still over 2%. A log-normal check on the reliability calculation shows that the FORM/SORM solution matches the analytical result well. However, the log-normal model is highly non-conservative.

References

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