Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 158 (2019) 3729–3734

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Application of gamma process and maintenance cost for fatigue damage of wind turbine blade

Chizhi Zhang[a], Kong Fah Tee[a,*]

[a]*Department of Engineering Science, University of Greenwich, Chatham Maritime, Kent, ME4 4TB, UK*

Abstract

The blades of offshore wind turbines accumulate structural damage such as fatigue due to aerodynamic loading by various wind speeds during their service time, leading to premature structural failures. This paper investigates the fatigue damage by the blade element momentum theory (BEMT) method and the cost of operation and maintenance by the integrating models. Three prediction models have been proposed for lifetime performance assessment and management of wind turbine blade, i.e. fatigue prediction model (FPM), the reliable stochastic model (SRM) and cost benefit model (CBM). The fatigue model is discussed to reproduce the fatigue damage evolution in composite blades subjected to aerodynamic loadings by cyclical winds. The lifetime probability of fatigue failure of the composite blades is estimated by stochastic deterioration modelling such as gamma process. On the basis of the cost model, an optimised maintenance policy is determined to make optimal maintenance decision for the composite blades. A numerical example is employed to investigate the effectiveness of predicting fatigue damage and estimating the probability of fatigue failure to determine an opportunistic maintenance policy. The results from the numerical study show that the stochastic gamma process together with the fatigue models can provide a useful tool for remaining useful life predictions and optimum maintenance strategies of the composite blades of offshore wind turbines.

Keywords: Wind turbine blade, Fatigue, Stochastic Modelling, Cost model, Reliability

1. Introduction

With the higher requirement of sustainable energy, wind farms have become one of the most popular clean and renewable power in developed countries. As one typical offshore structures, wind turbines are suffered from the harsh marine environments and cyclic wind loadings during the design life, and the operation and maintenance take up nearly 30% of lifecycle costs [1]. According to the field failure data from various databases, it shows that the blades are the most critical component in offshore wind turbine and suffer from a high failure rate. Therefore, it is vital to select an

* Corresponding author.
E-mail address: K.F.Tee@gre.ac.uk

10.1016/j.egypro.2019.01.884

effective prediction fatigue model in order to evaluate the fatigue damage performance of the blades based on aerodynamic load by wind speed.

For analysing the aerodynamic load calculation, the blade element momentum theory (BEMT) is simple, and is still widely used for practical engineering application of wind turbine blade at present [2, 3]. In order to improve the accuracy, the BEMT method has been optimised and modified to provide increasingly accurate results, and the latest corrections for the BEMT model are the turbulent wake state by Buhl [4] and the tip-hub loss by Shen [5]. To develop specific stress-strain curves of the composite structure, the FE model of wind turbine blade can be combined with results of aerodynamic loads from the BEMT method by applying forces and moments in each element of the FE model. The most investigations on fatigue phenomena of wind turbine blades use load spectra from wind speed spectra generated by the Weibull distribution, giving numerical estimates at a location near the root of the blade. Then, to obtain the cycles, traditional counting methods such as Rainflow counting is widely used in recent research. Based on the Goodman diagram and S-N curve, the equivalent load spectra for each cycle can be estimated [6]. This calculated stress is then utilised to estimate fatigue damage in the blade using Reifsnider model, and then the predicted fatigue life is estimated for optimal maintenance strategies [7].

In previous studies, the gamma process has been considered as an appropriate stochastic approach to simulate the stochastic deterioration process, such as fatigue damage of wind turbine blades [8]. The evolution of fatigue damage for wind turbine blades can be modelled as a stochastic process because of uncertainties in offshore environments. Considering the nature of cumulative growth of fatigue damage by Reifsnider model, the gamma process model is an appropriate approach for deterioration since gamma process has been proved to be more versatile and increasingly used in optimal maintenance strategies. On the basis of stochastic deterioration modelling, a cost-effective model is proposed for the rational and optimal planning of maintenance actions for composite blades of offshore wind turbines.

As previously indicated, a combined approach integrating the FPM, SRM, and CBM model is herein proposed for lifetime structural performance assessment and management associated with fatigue damage of wind turbine blade. The existing data and the approach of [6] are used to develop the FPM for the time-dependent fatigue reliability evaluation, while the stochastic method information from [7] and the cost prediction is used to develop the SRM and CBM model. The proposed approach is illustrated on an existing blade in the FE model, the NREL 5 MW wind turbine blades. From the results, the proposed method can both provide a useful tool for evaluating the performance of a wind turbine blade and assessing fatigue damage of the wind turbine blades with a wide range of wind velocities.

Nomenclature

v	shape parameter for gamma process
u	scale parameter for gamma process
$\Gamma(v)$	complete gamma function
$D(t)$	fatigue damage at t time
D	fatigue damage
N	fatigue cycles
η, ζ	Reifsnider model parameters
C_d	the expected discounted costs
C_P	preventive maintenance cost
C_F	corrective maintenance cost

2. Fatigue prediction model

The fatigue prediction model is based on the BEMT method applying in the FE model, and then the structural analysis is proposed. The aerodynamic loading for wind turbine blade is based on the BEMT with latest corrections, which obtains the thrust acting on the blade as well as the torque. The normal force, tangential force and pitching moment along with the global coordinate of the blade need to be calculated for the FE model based on the results of the BEMT established for different wind speeds [9]. Then the maximum stress in the blade is investigated by the results of the FE model of wind turbine blades. Fatigue life is estimated by a new fatigue model for accumulating the damage based on the Goodman diagram and S-N curve. By FPM, a dynamic structural problem for the fatigue can be converted into a static structural problem, which is easier to be solved. The details of this processing are presented in the previous study [6].

3. Stochastic reliability model

Gamma process is a stochastic process with an independent non-negative gamma distribution increment with identical scale parameter monotonically accumulating over time in one direction, which is suitable to model gradual damage such as wear, fatigue, corrosion, erosion. Gamma process with uncertainties is a stochastic process and should be an effective approach for simulating the deterioration process. Thus, it can be considered as a time-dependent stochastic process $\{X(t), t\geq 0\}$ where $X(t)$ is a random quantity for all $t\geq 0$.

The gamma process is a continuous stochastic process $\{X(t), t\geq 0\}$ with the following three properties: (1) $X(t)=0$ with probability one; (2) $X(t)$ has independent increments; (3) $X(t)-X(s)\sim Ga(v(t-s),u)$ for all $t>s\geq 0$. [4, 10]

The probability density function $Ga(x|v,u)$ is given by

$$Ga(x|v,u) = \frac{u^v}{\Gamma(v)} x^{v-1} e^{-ux} I_{(0,\infty)}(x) \tag{1}$$

where v is shape parameter; u is scale parameter, and $I_{(0,\infty)}(x)=1$ for $x\in(0,\infty)$, $I_{(0,\infty)}(x)=0$ for $x\notin(0,\infty)$; and the complete gamma function $\Gamma(v)$ for $v\geq 0$ is defined as

$$\Gamma(v) = \int_0^\infty x^{v-1} e^{-x} dx \tag{2}$$

The function v must be an increasing, right-continuous real-valued function of time t, with $v(0) \equiv 0$ to facilitate the monotonic nature of deterioration over time. The cumulative deterioration at times t_i and t_{i-1} are $X(t_i)$ and $X(t_{i-1})$, respectively. Using the fatigue damage $D(t)$ to replace the v function, the probability density function can be written as:

$$X(t_2) - X(t_1) = Ga(D(t_i) - D(t_{i-1}), u) = \frac{u^{D(t_i)-D(t_{i-1})}}{\Gamma(D(t_i)-D(t_{i-1}))} x^{D(t_i)-D(t_{i-1})-1} e^{-uD} I_{(0,\infty)}(D) \tag{3}$$

The mean, variance, and coefficient of variation of the cumulative deterioration at time t are given as

$$\mu_{X(t)} = \frac{D(t)}{u} \qquad \sigma_{X(t)} = \frac{\sqrt{D(t)}}{u} \qquad v_{X(t)} = \frac{1}{\sqrt{D(t)}} \tag{4}$$

where the coefficient of variation is a time-dependent function and is inversely proportional to the time.

The equation for the failure probability can be calculated from

$$F(t) = P\{X(t) \geq X(t_N)\} = P\{X(t) \geq \rho\} = \int_\rho^\infty f(D)dD = \frac{\Gamma(D(t),u\rho)}{\Gamma(D(t))} \tag{5}$$

where the ρ is the critical damage according to design code. In modelling the temporal variability of the deterioration with a gamma process, the mean deterioration at time t is often proportional to a power law, such as exponential function is used in the most study.

However, the new fatigue damage evolution following a new non-linear mathematic law is used in this study for composite materials, and the development of the fatigue process is shown in Fig. 1.

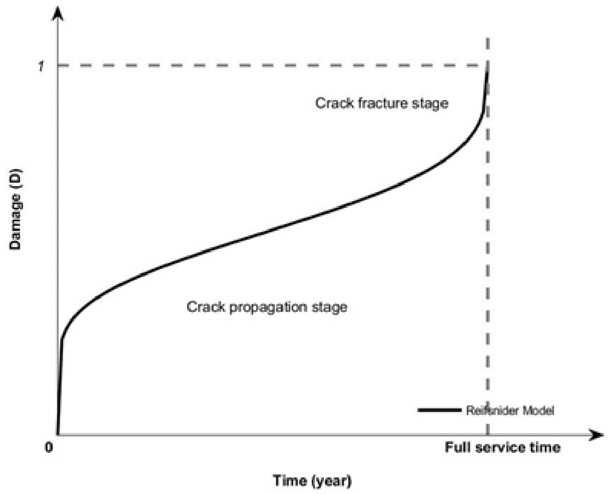

Fig. 1. A schematic of the typical Reifsnider model for fatigue damage evolution

The new fatigue damage model for composites has been widely investigated theoretically and experimentally, and it can be used to predict the fatigue damage growth within the period of the fatigue lifetime. The damage evolution equation for composite blades can be written as

$$D = 1 - (1 - \left(\frac{n_i}{N}\right)^{\eta})^{\zeta} \tag{6}$$

$$\Delta D = (1 - \left(\frac{n_{i-1}}{N}\right)^{\eta})^{\zeta} - (1 - \left(\frac{n_i}{N}\right)^{\eta})^{\zeta} \tag{7}$$

where η, ζ are model parameters, respectively. The fatigue damage D_i is 0 when $n_i = 0$ and reaches the critical damage *1* when $n_i = N$.

The fracture stage occurs when the damage has developed to the final stage under cyclic loading. Then, the structure becomes unstable, and the release of strain energy is sufficient to make the damage self-propagate until complete disruption and failure occurrence. Once the fracture stage is reached, failure will occur whether or not the stress is increased. This stage starts after the uncontrolled damage development exceeds the unit of damage value and reflects in the overall expansion of the structure, as shown in Fig. 1. When it occurs, the whole structure could not resist any further stress, leading to the structural failure.

4. Cost benefit model

Maintenance can be modelled as a discrete time renewal process, whereby the renewals bring a structure back to its original condition. Two typical types of maintenance are often used: preventive maintenance before failure and corrective maintenance after failure. The cost benefit model is based on renewal theory, the expected discounted costs at different dates over time intervals (0, k] are related to the preventive maintenance cost C_P, the corrective maintenance cost C_F, and the expected renew fatigue damage

$$C_d(k) = \frac{\alpha^i\left(\sum_{i=1}^{k} F(t)\right)C_F + \alpha^k\left(1 - \sum_{i=1}^{k} F(t)\right)C_p}{1 - \alpha^i\left(\sum_{i=1}^{k} F(t)\right) + \alpha^k\left(1 - \sum_{i=1}^{k} F(t)\right)} \tag{8}$$

where k = 1, 2, 3… represents the number of time intervals to be determined; a = 1/(1 + r) is the discount factor per unit time, and r is the discount rate per unit time. The optimal maintenance time interval k* is then obtained by minimising the expected discounted costs over a lifetime [11].

5. Application

5.1. Geometry and results of fatigue prediction model

In order to assess the accuracy of the performance analysis of the above method, the 5 MW blade developed by the National Renewable Energy Laboratory (NREL) is used as the reference model, and FE model analyses the performance of the blade. This composite blade considered in this study is the same geometry as the NREL 5 MW reference wind turbine composite blade. The NREL 5 MW reference wind turbine is a conventional three-bladed upwind turbine based on the NREL report. According to the existing study, the five cumulative fatigue life results have been investigated by FPM [6], listed below.

Table 1. The fatigue life results of NREL 5 MW reference wind turbine [6].

No.	1	2	3	4	5
Fatigue life	27.48	31.71	28.66	36.28	30.24

From the inspection data of these wind turbine blades discussed previously, the superstructure data are fitted to the gamma distribution.

5.2. Gamma parameter estimation of the stochastic reliability model

Because of the inconsistency observed in this basic nonlinear method, it is decided to use a maximum likelihood [10] method for parameter estimation of the gamma distribution (with 95% confidence interval). The D value is 106.3376 and u is 0.2903. The CDFs with different acceptable ρ at various points at time t, derived based on the estimated shape and scale parameters, are shown in Fig. 2. The CDF indicates the relative probability of failure at different times t at each of the values in deterioration.

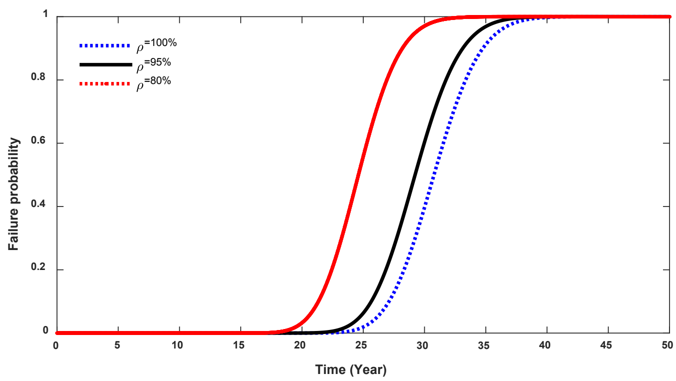

Fig. 2. Failure probability for different critical damage limitations based on gamma process

The results of the lifetime failure probability are shown in Fig. 2 for three different critical delamination length limits, i.e. ρ =100%, 95%, 80%, respectively. The shapes of failure probability curves for different critical delamination length are similar. The probability of failure associated with the critical delamination length depends on the given acceptable limit, with a higher probability of failure for a lower acceptable level at any given time and vice versa. The time of failure probability reaching unity is close for these three predefined critical delamination lengths where the blade needs to be repaired or replaced.

5.3. Maintenance strategies and cost benefit model

In a preventive replacement policy, the blade is replaced when it reaches a specific age regardless of its condition. It is based on the preventive age replacement policy that minimises the long-run average cost. The gamma process model cumulative fatigue lifetime distributions together with expected average cost per unit time presented in Eq. (8) can be used with a preventive replacement policy to identify the optimal time to replace the building element. Fig. 3 illustrates the derivation of optimal age-based replacement. In this example, the cost model uses the ratio of 1:5 for the preventive replacement cost: replacement cost (C_p:C_F) ratio. As shown in Fig. 3, the optimal age for replacement is identified as 17 years. This is the time at which long-run average cost per unit time is minimised.

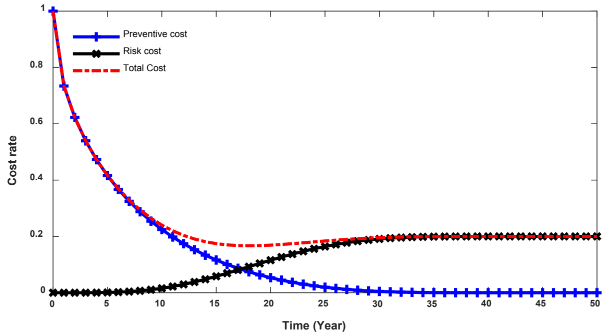

Fig. 3. Maintenance cost of reliability based on gamma process

6. Conclusions

This study uses a stochastic method to analyse fatigue damage evolution processes for the composite blades of offshore wind turbines. A numerical case study is presented to investigate the effectiveness of the stochastic deterioration modelling with different fatigue damage development model. The results show that stochastic fatigue damage modelling gives reliable results and can be used for analysing the failure probabilities of composite blades. The proposed stochastic modelling methods evaluate reasonably the lifetime distribution of probability of failure for composite blades and can be used to assist in the inspection and maintenance of composite blades in operation.

The proposed optimum maintenance strategy based on the reliability analysis and lifecycle cost analysis can give a balance between the extended service life and the total cost for maintenance of the composite blades. The proposed methods will be more cost-effective for repairing the composite blades experienced fatigue when the interventions are conducted at the early stage of the fatigue damage propagation.

References

[1] J. J. Nielsen and J. D. Sørensen, “On risk-based operation and maintenance of offshore wind turbine components,” *Reliab. Eng. Syst. Saf.*, vol. 96, no. 1, pp. 218–229, 2010.
[2] R. Lanzafame and M. Messina, “Advanced brake state model and aerodynamic post-stall model for horizontal axis wind turbines,” *Renew. Energy*, vol. 50, pp. 415–420, 2013.
[3] J. R. P. Vaz, J. T. Pinho, and A. L. A. Mesquita, “An extension of BEM method applied to horizontal-axis wind turbine design,” *Renew. Energy*, vol. 36, no. 6, pp. 1734–1740, 2011.
[4] M. L. Buhl Jr, “New Empirical Relationship between Thrust Coefficient and Induction Factor for the Turbulent Windmill State,” 2005.
[5] W. Z. Shen, R. Mikkelsen, J. N. Sørensen, and C. Bak, “Tip loss corrections for wind turbine computations,” *Wind Energy*, vol. 8, no. 4, pp. 457–475, 2005.
[6] C. Zhang, H.-P. Chen, and T.-L. Huang, “Fatigue damage assessment of wind turbine composite blades using corrected blade element momentum theory,” *Meas. J. Int. Meas. Confed.,* Under review
[7] H.-P. Chen, C. Zhang, and T.-L. Huang, “Stochastic modelling of fatigue crack evolutions in composite blades of offshore wind turbines,” *Struct. Eng. Mech.*, vol. 6, no. 63, pp. 703–712, 2017.
[8] J. M. van Noortwijk, “A survey of the application of gamma processes in maintenance,” *Reliab. Eng. Syst. Saf.*, vol. 94, no. 1, pp. 2–21, 2009.
[9] J. M. Mejía, F. Chejne, R. Smith, L. F. Rodríguez, O. Fernández, and I. Dyner, “Simulation of wind energy output at Guajira, Colombia,” *Renew. Energy*, vol. 31, no. 3, pp. 383–399, 2006.
[10] R. Edirisinghe, S. Setunge, and G. Zhang, “Application of Gamma Process for Building Deterioration Prediction,” *J. Perform. Constr. Facil.*, vol. 27, no. 6, pp. 763–773, 2013.
[11] H. P. Chen and A. M. Alani, “Optimized maintenance strategy for concrete structures affected by cracking due to reinforcement corrosion,” *ACI Struct. J.*, vol. 110, no. 2, pp. 229–238, 2013.