Probabilistic Engineering Mechanics 41 (2015) 139–154

Contents lists available at ScienceDirect

Probabilistic Engineering Mechanics

journal homepage: www.elsevier.com/locate/probengmech

Fatigue damage evaluation of broad-band Gaussian and non-Gaussian wind load effects by a spectral method

Jie Ding, Xinzhong Chen *

National Wind Institute, Department of Civil and Environmental Engineering, Texas Tech University, TX, United States

A R T I C L E I N F O

Article history:
Received 9 March 2015
Accepted 19 June 2015
Available online 22 June 2015

Keywords:
Fatigue damage evaluation
Rainflow cycle counting
Non-Gaussian fatigue
Spectral method
Tall buildings
Roof claddings
Wind load effects

A B S T R A C T

This study presents fatigue damage evaluation of broad-band Gaussian and non-Gaussian wind load effects by a spectral method proposed in Benasciutti and Tovo (2005) [4]. The wind load effects considered are alongwind, crosswind and their coupled responses of tall buildings, and wind pressures on claddings. Following this spectral method, the rainflow counting damage is approximated by a linear combination of its upper and lower bounds. A refined formulation for determining the combination factor is proposed, which depends on bandwidth parameters in terms of process spectral moments. For non-Gaussian wind load effects, research emphasis is placed on the modeling of translation function which relates the non-Gaussian process with an underlying Gaussian process and is essential for non-Gaussian fatigue damage evaluation. Both moment-based translation model and the model by a direct curve fitting are addressed for a wide range of non-Gaussian characteristics, including a newly developed translation model for hardening non-Gaussian processes. The effectiveness and accuracy of the spectral method for broad-band Gaussian and non-Gaussian processes are demonstrated through comparison with the results from time domain rainflow counting method.

1. Introduction

Stochastic wind load effects on structures may lead to accumulation of fatigue damage and result in failure of structural components and system. The wind-induced fatigue and extreme load effects are two limit-state responses important for design consideration of wind-excited structures [24,31,33,34,37,44,13,6,7].

When the stress time history is available, time domain approaches can be applied for fatigue damage evaluation. The cycle number as a function of stress amplitude, often referred to as fatigue loading spectrum, is estimated using a cycle counting method. The cumulative fatigue damage is then determined using Palmgren–Miner rule with S–N curve. A number of approaches have been developed for cycle counting, including peak counting, level-crossing counting, range-mean counting and rainflow counting methods [17,2,35]. Among them, the rainflow counting method provides a better estimation for general stochastic processes, and has been accepted as a standard cycle counting method in fatigue analysis (e.g., [2,44,26]). However, the construction of a reliable cycle distribution relies on a sufficient length of stress time history, which is not always available in engineering practice.

Alternatively, the cycle counting and fatigue damage analysis can be performed using frequency domain approaches, which develop analytical formulae from process power spectral density (PSD) function. In the case of narrow-band Gaussian processes, the cycle distribution is readily determined from Rayleigh distribution of process amplitude, and the fatigue damage is then calculated by a closed-form expression. However, the fatigue damage from this approximation can be very conservative as compared to the rainflow counting damage when the stress process is not narrow-banded. Various approaches have been developed for broad-band Gaussian processes to approximate rainflow counting damage taking into account the spectral properties [19,29,38,43,46]. For instance, a correction factor was introduced by Wirsching and Light [43] to characterize the difference between narrow-band approximation and rainflow counting method. Another simple correction was proposed by Lutes and Larsen [29], which is referred to as single-moment method since the correction depends on only one spectral moment. The method proposed by Jiao and Moan [25] was for broad-band Gaussian processes with low-frequency and high-frequency bimodal spectral formulation. This method has been refined by Gao and Moan [19] for Gaussian processes with a trimodal spectrum. Directly seeking an approximation to rainflow amplitudes was attempted by several researchers (e.g., [16,46,3]), among which the most accurate and wildly used empirical formulations are considered to be the ones proposed by Dirlik [16], Zhao and Baker [46]. Tovo [38] provided

* Corresponding author.
E-mail addresses: jie.ding@ttu.edu (J. Ding), xinzhong.chen@ttu.edu (X. Chen).

http://dx.doi.org/10.1016/j.probengmech.2015.06.005
0266-8920/

another approximation to rainflow counting damage, which estimates the fatigue damage as a proper intermediate point between its upper and lower bounds defined by level-crossing counting and range-mean counting methods, respectively. The advantage of this method is that an equivalent joint probability distribution function (JPDF) of peak and valley can be obtained [5]. It facilitates further considerations of mean stress effect and also non-Gaussian characteristics of a stress process in fatigue damage evaluation.

Spectral methods for fatigue analysis of non-Gaussian processes have also been addressed in literature [18,28,4,40], primarily focusing on softening non-Gaussian processes with kurtosis larger than 3, which lead to accelerated fatigue damage than Gaussian processes. The non-Gaussian process can be modeled as a translation process from an underlying Gaussian process through a monotonic increasing translation function [21,22,40]. Subsequently, the occurrence of peak and valley in the underlying Gaussian process is always simultaneous as in the non-Gaussian process due to the monotone property of translation. Therefore, the distribution of peak and valley for the non-Gaussian process can be determined if the one for its underlying Gaussian process is specified. In the case of narrow-band unskewed non-Gaussian processes, a closed-from correction as a function of process kurtosis was introduced for the fatigue analysis from that of underlying Gaussian process [30,40]. A more accurate correction was recently introduced in Chen [7] for narrow-band unskewed hardening non-Gaussian processes with kurtosis less than 3. The accuracy and effectiveness of the fatigue analysis methods for non-Gaussian processes based on translation process theory depend on the adequacy of the equivalent JPDF of peak and valley of underlying Gaussian process and the modeling of translation function. Considering various broad-band spectral properties and non-Gaussian distribution characteristics, the spectral methods for fatigue analysis of broad-band non-Gaussian processes warrant further investigation.

Concerning the fatigue damage analysis of wind-excited structures, Holmes [24] derived closed-form expressions for upper and lower limits of fatigue damage of alongwind response. The upper limit was achieved by narrow-band approximation, while the lower one was obtained based on the correction factor proposed by Wirsching and Light [43]. However, as pointed out by Lutes et al. [28] and Repetto and Solari [34], the damage correction factor proposed by Wirsching and Light [43] may underestimate or overestimate the real damage, depending on the spectral shape of the stress process. Repetto and Solari [33] addressed fatigue damage of coupled alongwind and crosswind response using the approach developed by Jiao and Moan [25]. The fatigue damage of alongwind response with both broad-band background (quasi-static) response and narrow-band resonant response components was studied in Repetto and Solari [34]. While the fatigue damage of broad-band wind load effects on roof claddings have been investigated using rainflow counting method [26,44], the adequacy of the spectral methods for fatigue damage associated with broad-band Gaussian and non-Gaussian wind load effects has not yet been extensively explored. Full-scale and wind tunnel measurement data have shown that the wind pressures on claddings may be of significant non-Gaussian characteristics (e.g., [23,45,26]). The application of translation process theory to non-Gaussian wind pressures faces many challenges in better modeling the translation functions and their extreme value distributions [14]. Similar challenges are expected for the fatigue analysis of broad-band non-Gaussian processes in addition to the influence of spectral properties.

In this study, the spectral method introduced in Benasciutti and Tovo [4], referred to as TB spectral method, is re-evaluated for fatigue analysis of broad-band Gaussian and non-Gaussian wind load effects. The wind load effects considered are alongwind, crosswind and their coupled responses of tall buildings, and wind pressures on claddings. The accuracy of the TB spectral method is examined through comparison with rainflow counting damage estimated from sufficient long time history samples. A refined formulation is proposed to account for the influence of spectral shape on fatigue damage. For non-Gaussian wind load effects, research emphasis is placed on the modeling of translation function which relates the non-Gaussian process to an underlying Gaussian process and is essential for non-Gaussian fatigue damage evaluation. The results demonstrate the effectiveness and accuracy of the spectral method developed for broad-band Gaussian and non-Gaussian processes.

2. Spectral method for fatigue analysis of Gaussian processes

2.1. Narrow-band Gaussian processes

For a very narrow-band stress process $X(t)$, it is reasonable to state that a stress cycle is formed by a peak and the following symmetrical valley, and the amplitude equals to the value of peak if the process is of zero mean. Therefore, the peak counting, level-crossing counting, range-mean counting and rainflow counting methods result in the same cycle distribution. Furthermore, the probability distribution of amplitude (or range) is identical to that of the peaks, and follows a Rayleigh distribution:

$$p(s) = \frac{s}{\sigma_X^2} e^{-\frac{s^2}{2\sigma_X^2}} \tag{1}$$

where s is the stress amplitude; and σ_X is standard deviation (STD) of the stress process.

The number of cycles per unit time (υ_a) can be taken as the occurrence rate of upcrossings at mean level (υ_0), then the mean fatigue damage per unit time, i.e., mean damage rate ($E[D_{NB}]$), is estimated as [32]

$$E[D_{NB}] = \upsilon_a C^{-1} \int_0^\infty s^k p(s) ds = \upsilon_0 C^{-1} (\sqrt{2}\sigma_X)^k \Gamma(1+\frac{k}{2}) \tag{2}$$

where the S–N curve defined as $N(s) = Cs^{-k}$ is applied; $\Gamma()$ is the gamma function defined as $\Gamma(t) = \int_0^\infty x^{t-1}e^{-x}dx$; υ_0 can be determined from spectral moments as

$$\upsilon_0 = \frac{1}{2\pi}\sqrt{\frac{\lambda_2}{\lambda_0}} \tag{3}$$

$$\lambda_n = \int_0^\infty (2\pi f)^n S_X(f) df \tag{4}$$

and λ_n is nth moment of the process PSD, $S_X(f)$; and f is frequency in Hz.

2.2. Broad-band Gaussian processes

It is well-known that for a broad-band Gaussian process, the fatigue damage estimated from Rayleigh distribution of amplitude (narrow-band approximation) is very conservative with comparison to rainflow counting damage [35]. However, an explicit analytical distribution function for rainflow cycles of a broad-band process is not available so far due to the complex definition of this algorithm [17]. In this section, the approach introduced by Tovo [38], and Benasciutti and Tovo [4], referred to as TB spectral method, is discussed, which provides an equivalent JPDF of peak and valley for rainflow counting method, and facilitates its application to non-Gaussian processes.

For a stationary Gaussian process, it is widely accepted that the fatigue damage rate calculated from rainflow counting method,