Engineering Structures 74 (2014) 145–156

Contents lists available at ScienceDirect

Engineering Structures

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

Analysis of crosswind fatigue of wind-excited structures with nonlinear aerodynamic damping

Xinzhong Chen *

National Wind Institute, Department of Civil and Environmental Engineering, Texas Tech University, Lubbock, TX 79409, USA

ARTICLE INFO

Article history:
Received 10 January 2014
Revised 2 April 2014
Accepted 30 April 2014
Available online 6 June 2014

Keywords:
Crosswind response
Vortex-induced vibration
Nonlinear aerodynamic damping
Non-Gaussian fatigue
Rainflow cycle counting method
Spectral method
Tall building
Wind loads

ABSTRACT

This study addresses crosswind fatigue analysis of wind-excited flexible structures at the vicinity of vortex lock-in speed where the nonlinear aerodynamic damping effect is significant. The nonlinear aerodynamic damping is modeled as a polynomial function of time-varying displacement or velocity of vibration. The crosswind response is a narrow-band hardening non-Gaussian process with a reduced peak factor and having a distribution of vibration amplitude different from Rayleigh distribution. Analytical solutions of cycle number and fatigue damage are derived and their accuracy is validated through comparison with rainflow cycle counting method using simulated response time histories. A correction factor as a function of response kurtosis is also introduced that facilitates the calculation of non-Gaussian fatigue damage from the Gaussian fatigue prediction. The effectiveness and accuracy of the proposed framework are illustrated by crosswind responses of a squared tall building and a two-dimensional structural section model, and by full-scale vibration measurement data of a traffic-signal-support-structure. This study provides an improved estimation of crosswind fatigue of wind-excited flexible structures with a consideration of hardening non-Gaussian response character.

1. Introduction

Wind-induced fatigue of flexible structures is one of the important limit-state responses for structural design consideration. The fatigue damage and fatigue life of wind-excited structures can be predicted by integrating the fatigue analysis conditional on wind speed and direction with the joint probability distributions of wind speed and direction (e.g., [25,42]). When wind-induced stress time histories under given wind speed and direction are available, the cycle counting methods are used to estimate the cycle number as a function of stress range, often referred to as fatigue loading spectrum. The cumulative fatigue damage is then determined using Palmgren–Miner rule based on S–N curve [36]. The S–N curve describes the number of cycles to failure for a given stress range which is developed through fatigue strength tests with different stress ranges. Several cycle counting methods have been developed, including peak counting, range counting and rainflow counting methods [35,17,45]. These three methods give the same result for a pure sinusoidal stress history and for an ideal narrow-band stress history. The rainflow counting method, however, provides an improved estimation for more general stochastic processes, and has been accepted as a standard cycle counting method in fatigue analysis (e.g., [57,31,2]).

The cycle counting and fatigue analysis can also be made using spectral methods based on the knowledge of power spectral density (PSD) function of the stress process. The spectral methods are computationally more effective over the time domain cycle counting method. The narrow-band approximation method is the most widely used spectral method due to its simplicity. It provides a closed-form solution for the fatigue analysis based on the Rayleigh distribution of response amplitude. This method has been applied to crosswind fatigue analysis (e.g., [19,14,41]), and may also be used for alongwind fatigue analysis of flexible structures when the narrow-band resonant response is dominant. However, the Rayleigh predictions can be very conservative as compared to the rainflow predictions when the stress process is not narrow-banded [52,33,4,22,37]. It fails to result in accurate prediction for alongwind response with both broad-band background (quasi-static) response and narrow-band resonant response components [40], and for coupled alongwind and crosswind vibration [42].

For more general broad-band processes, the ideal spectral method is to develop a closed-form solution or simple approximation for the probability distribution of rainflow ranges [34]. Currently, this problem remains an open challenging issue as it faces a difficulty in finding the joint probability distribution of the

* Corresponding author. Tel.: +1 806 834 6794; fax: +1 806 742 3488.
E-mail address: xinzhong.chen@ttu.edu

http://dx.doi.org/10.1016/j.engstruct.2014.04.049
0141-0296/

sequence of process extrema. Several spectral methods have been developed for stationary Gaussian broad-band response processes. The methods proposed by Dirlik [16] and by Zhao and Baker [58] have been confirmed to give results close to the predictions from the rainflow counting method [8,6]. Repetto and Solari [43] adopted the method proposed by Jiao and Moan [26] for alongwind fatigue analysis of wind-excited structures. This method has been refined by Gao and Moan [22] for broad-band stationary Gaussian processes with a trimodal spectral formulation. The fatigue analysis of alongwind response with background and resonant response components were also addressed in Patel and Feathy [39], Wyatt [55,56], Petrov [38], and Holmes [25]. In Holmes [25], closed-form solutions from both narrow-band approximation method and the method proposed by Wirsching and Ligh [52] were presented. Spectral methods for fatigue analysis of non-Gaussian processes have also been addressed in literature [32,53,5,21], primarily focusing on softening non-Gaussian processes with kurtosis larger than 3, which lead to accelerated fatigue damage than Gaussian processes.

Crosswind response excited by separation and vortex shedding of the wake flow and wind turbulence is an important and often dominant component for wind-resistant design of tall buildings and flexible structures (e.g., [27,30,28,7]). As revealed by Chen [10–12], attributed to the amplitude-dependent nonlinear aerodynamic damping effect at the vicinity of vortex lock-in speed, the crosswind response shows a hardening non-Gaussian process property, whose peak factor is much lower than that of traditional Gaussian response and the distribution of vibration amplitude is apparently different from Rayleigh distribution. Chen [10] presented complete analytical solutions of crosswind response statistics when the aerodynamic damping is modeled as a polynomial function of time-varying displacement or velocity, including not only root-mean-square (RMS) response, i.e., standard deviation (STD), but also response kurtosis, probability distributions of vibration displacement and amplitude, peak factor and extreme value distribution.

This study further addresses the crosswind fatigue analysis of flexible structures at the vicinity of vortex lock-in speed. Analytical solutions of cycle counting and fatigue analysis associated with narrow-band hardening non-Gaussian crosswind response are derived following the framework presented in Chen [10]. The accuracy of the analytical framework is validated through comparison with rainflow counting method using simulated response time histories. A correction factor as a function of response kurtosis is also introduced which facilitates the calculation of non-Gaussian fatigue damage from the Gaussian fatigue prediction. The effectiveness and accuracy of the proposed framework are illustrated by crosswind responses of a squared tall building and a two-dimensional structural section model, and by full-scale vibration measurement data of a traffic-signal-support-structure. It should be mentioned that while the effect of nonlinear aerodynamic damping on the crosswind RMS response has been accounted in literature [14,42,19,24], the narrow-band crosswind fatigue analysis has been based on Rayleigh distribution of vibration amplitude. The crosswind fatigue analysis with a consideration of hardening non-Gaussian response character has not yet been addressed.

2. Theoretical framework

2.1. Equation of motion of crosswind response

The equation of crosswind response of a wind-excited structure in terms of modal displacement of interest is expressed as

$$\ddot{y} + 2\xi_s\omega_s\dot{y} + \omega_s^2 y = \frac{1}{2}\left(\frac{\rho B^2}{m_s}\right)\left(\frac{U^2}{B^2}\right)\eta(C_{Qse}(t) + C_{Qb}(t)) \tag{1}$$

$$m_s = \frac{\int_0^H m(z)\phi^2(z)dz}{\int_0^H \phi^2(z)dz}; \quad \eta = \frac{H}{\int_0^H \phi^2(z)dz} \tag{2}$$

where $y = y_1/B$ is normalized non-dimensional displacement; y_1 is generalized crosswind displacement and the displacement at location z is $\phi(z)y_1$; $\phi(z)$ is mode shape; $\omega_s = 2\pi f_s$ and ξ_s are modal frequency and damping ratio; $m(z)$ is mass per unit length at location z; m_s is effective mass per unit length; $C_{Qse}(t)$ and $C_{Qb}(t)$ are self-excited (motion-induced) and buffeting components of generalized crosswind force coefficient; ρ is air density; U is wind speed at a reference location, say, at the building top in the case of tall building; B is representative structural width; and H is structural length or height; and η is a non-dimensional parameter related to mode shape, and $\eta = 3$ for a linear mode shape $\phi(z) = z/H$.

The self-excited force coefficient $C_{Qse}(t)$ is often determined using forced-vibration model testing in wind tunnel. The structural model is forced to have a harmonic vibration $y(t) = y_1(t)/B = y_{\max}\sin(\omega t)$, the corresponding generalized self-excited force coefficient $C_{Qse}(t)$ is measured and is expressed in terms of vibration displacement and velocity as

$$C_{Qse}(t) = KH_1^*\frac{B\dot{y}}{U} + K^2H_4^*y \tag{3}$$

where $K = \omega B/U$ is reduced frequency and $2\pi/K = U/fB$ is reduced wind speed; H_1^* and H_4^* are aerodynamic derivatives and are functions of reduced frequency, representing out-of-phase (damping) and in-phase (stiffness) components with displacement, respectively. At the vicinity of vortex lock-in speed, the self-excited force shows a noticeable nonlinear dependence on vibration amplitude $y_{\max} = y_{1\max}/B$. The aerodynamic derivatives H_1^* and H_4^* are functions of both reduced frequency and amplitude $y_{\max}$, i.e., $H_1^* = H_1^*(K, y_{\max})$ and $H_4^* = H_4^*(K, y_{\max})$.

The influence of aerodynamic stiffness on structural frequency is generally very small, thus can be neglected. The equation of motion is represented as

$$\ddot{y} + 2(\xi_s + \xi_a)\omega_s\dot{y} + \omega_s^2 y = \frac{1}{2}\left(\frac{\rho B^2}{m_s}\right)\left(\frac{U^2}{B^2}\right)\eta C_{Qb}(t) \tag{4}$$

where ξ_a is aerodynamic damping ratio, and is calculated as

$$\xi_a = -\frac{1}{4}\left(\frac{\rho B^2}{m_s}\right)\eta H_1^* \tag{5}$$

In the case of tall buildings, the generalized force is often estimated from base bending moment measured in wind tunnel with the high frequency force balance (HFFB) technique (e.g., [48,7,13]). The generalized force coefficients are given as

$$C_{Qse}(t) = \eta_{se}C_{Mse}(t); \quad C_{Qb}(t) = \eta_b C_{Mb}(t) \tag{6}$$

where $C_{Mse}(t)$ and $C_{Mb}(t)$ are self-excited and buffeting components of base bending moment coefficient; and η_{se} and η_b are mode shape correction factors. In the case of linear mode shape, i.e., $\phi(z) = z/H$, we have $\eta_{se} = \eta_b = 1$. In general, the mode shape correction factors depend on mode shape and also on the unknown distribution of dynamic wind loading, and thus are given empirically.

When crosswind response of a two-dimensional (2D) section model is considered, we have $\phi(z) = 1, \eta = 1$, and $C_{Qse}(t) = C_{Lse}(t)$ and $C_{Qb}(t) = C_{Lb}(t)$, where $C_{Lse}(t)$ and $C_{Lb}(t)$ are crosswind force coefficients.

2.2. Modeling of nonlinear aerodynamic damping

The aerodynamic damping shown in Eq. (5) determined from forced-vibration testing as a function of reduced frequency K and vibration amplitude of harmonic motion $y_{\max}$ is referred to as equivalent aerodynamic damping ratio and is denoted as ξ_{aeq}. This