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Analysis of buffeting response of hinged overhead transmission conductor to nonstationary winds

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ABSTRACT

This paper addresses analysis of dynamic buffeting response of a hinged transmission line (conductor) under nonstationary wind excitations. The nonstationary wind speed is characterized by deterministic time-varying mean and stochastic fluctuating components. The wind load on the conductor is quantified using quasi-steady theory. The wind-induced response of the conductor is decomposed into deterministic time-varying mean and stochastic dynamic components. The time-varying mean response is determined by nonlinear static analysis with an analytical solution. The stochastic dynamic response is determined through quasi-static analysis in terms of influence function around the time-varying mean equilibrium. A closed-form formulation is presented for calculating time-varying standard derivation of response. The cumulative distribution function of the extreme response over a given time duration is then calculate using mean upcrossing rate theory of nonstationary random process. The effectiveness and accuracy of the proposed analytical framework are verified through response time history analysis using a nonlinear finite element model. The response characteristics of conductor under various nonstationary winds are examined through a parametric study.

1. Introduction

Many transmission tower failures worldwide are reported to be attributed to the actions of localized non-synoptic winds, such as thunderstorm downbursts and tornadoes [26,34,20,39,6]. The wind flow field created by a non-synoptic wind can vary significantly from the traditional atmospheric boundary layer wind flows in terms of its unique mean wind speed profile, rapid time-varying mean wind speed, and spatially strongly correlated wind fluctuations [16,32,25,19]. Characterization and modeling of non-synoptic winds and their effects on structures through field observations, numerical, and physical simulations have received increasing attention in recent years [43,18,23,9,10, 24,27,1,41].

A number of studies have examined the non-synoptic wind load effects on transmission line structures using time-varying mean wind speed field generated by empirical models or computational fluid dynamics (CFD) simulations [36,37,8,38,20,12,13,17,15,2,4]. The wind load on the transmission line (conductor) is generally calculated from the wind fluctuation using quasi-steady theory. The system response is then calculated in the time domain using a finite element model (FEM) with consideration of structural geometric nonlinearity. Aboshosha and El Damatty [3,5] introduced an numerical iteration scheme using semi-closed and close-form solutions for predicting the nonlinear static conductor response under time-varying mean wind loads with arbitrary spatial distributions. Studies have shown that the wind loadings transmitted from the overhead conductor including the unbalanced dynamic tension are the main actions to the response of transmission towers. As large spatial structures with several hundreds of meters spans, the response of transmission line systems is affected by wind flow parameters such as wind speed profile, length scale, turbulence intensity and path of wind storms [39,6,15]. Previous studies have shown that the resonant dynamic response of conductor can be neglected because of the effect of large aerodynamic damping [31,28,12,6,42]).

This paper addresses the analysis of quasi-static (background) buffeting response of a conductor under nonstationary wind excitations. A transmission line system is composed of towers, insulators and conductors. In this study, the flexibility of towers and insulators are not included. The conductor is assumed to have fully-hinged boundary conditions as a hinged suspension cable. The support reactions of the conductor are considered as the external forces transmitted from conductor to towers. The frequencies of transmission towers are generally higher than the frequencies

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of the conductors (e.g., [44,7,35]). In addition, the deformation of towers is relatively small (e.g., [33]). Therefore, the influence of dynamic coupling between towers and conductors on quasi-static (background) response of conductors can be considered negligible. On the other hand, while the flexibility of the insulators can have a significant influence on the natural frequencies and mode shapes of the conductors, as the focus of this study is on the quasi-static response of the conductors, the influence of the flexibility of insulators is also neglected. This simplified modeling of transmission conductor as a hinged suspension cable is considered as a reasonably good approximation of realistic transmission line system, and has been widely used in literature and in design codes and specifications (e.g., [28,29,20]). The adequacy of this simplified model warrants further investigation. It should also be mentioned that the new findings of this study are for improved fundamental understanding of the quasi-static buffeting response of not only transmission conductors but also suspension cables under nonstationary wind excitations.

In the proposed analysis framework, the wind speed and conductor response are characterized by deterministic time-varying mean and stochastic fluctuating components. The wind load on the conductor is quantified from wind speed using quasi-steady theory. The time-varying mean response is calculated by nonlinear static analysis with an analytical solution. The stochastic dynamic response is considered as quasi-static (background) response whose time-varying standard derivation (STD) is calculated from response influence function and correlation function of wind fluctuation. The cumulative distribution function of the extreme response within a given time duration is then determined using mean upcrossing rate theory of nonstationary random process. It leads to the determination of peak factor and other percentile values of extreme response with given probabilities of exceedance. The effectiveness and accuracy of the proposed analytical framework are verified through response time history analysis using nonlinear FEM. The response characteristics of conductor under various nonstationary winds are examined through a parametric study. The proposed analysis framework will help to develop a useful tool for engineers involved in the design of transmission line under nonstationary wind excitations, which will be computationally more effective than the time domain FEM approach.

2. Response analysis framework

2.1. Modeling of nonstationary wind field and wind load

A horizontal transmission conductor hinged on both supports at the same elevation is considered. It is modeled as a uniform flat-sag suspended cable with a sag to span ratio of $1/30 \sim 1/50$. The initial line position under its gravity mg and a longitudinal tension H_0 is denoted as $y_0(x)$, which is a parabola with a sag d_0 as shown in Fig. 1, $y_0(x)$ and d_0 are expressed as

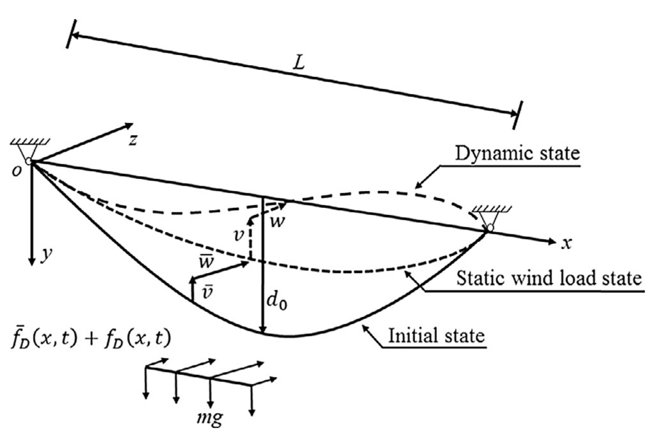

Fig. 1. Profile of the conductor under wind load.

$$y_0(x) = \frac{mg}{2H_0}x(L-x) \tag{1}$$

$$d_0 = \frac{mgL^2}{8H_0} \tag{2}$$

The mean wind speed is perpendicular to the initial conductor plan. The wind speed at the span-wise location x, $V_c(x,t)$, is a sum of deterministic time-varying mean wind speed component $\bar{V}(x,t)$ and random fluctuating component $V(x,t)$ as

$$V_c(x,t) = \bar{V}(x,t) + V(x,t) \tag{3}$$

The fluctuating component $V(x,t)$ is regarded as zero mean evolutionary (modulated) random process, and is expressed in the general form of a Fourier-Stilettoes integral representation as

$$V(x,t) = \int_{-\infty}^{\infty} g_V(x,\omega,t)e^{i\omega t}\mathrm{d}\Theta_V(x,\omega) \tag{4}$$

where $g_V(x,\omega,t)$ is modulation function and $g_V(x,\omega,t) = g_V^*(x,-\omega,t)$; and $d\Theta_V(x,\omega)$ is complex-valued zero mean orthogonal increment random process

$$E[\mathrm{d}\Theta_V(x,\omega)] = 0 \quad ; \mathrm{d}\Theta_V(x,\omega) = \mathrm{d}\Theta_V^*(x,-\omega) \tag{5}$$

$$E[\mathrm{d}\Theta_V(x_1,\omega_1)d\Theta_V^*(x_2,\omega_2)] = S_{V0}(x_1,x_2,\omega_1)\delta(\omega_1-\omega_2)d\omega_1 \tag{6}$$

$E[\,]$ is expectation or ensemble average; $\delta[]$ is Dirac delta function; $S_{V0}(x,x,\omega) = S_{V0}(x,\omega)$ and $S_{V0}(x_1,x_2,\omega)$ are the power spectral density (PSD) function and cross PSD function of the underlying stationary process of wind fluctuations; ω is frequency; superscript $*$ denotes complex conjugate operator; and $\mathrm{i} = \sqrt{-1}$.

The evolutional PSD (EPSD) of $V(x_1,t)$, and cross EPSD with $V(x_2,t)$ are then given as

$$S_V(x,\omega,t) = |g_V(x,\omega,t)|^2 S_{V0}(x,\omega) \tag{7}$$

$$S_V(x_1,x_2,\omega,t) = g_v(x_1,\omega,t)g_V^*(x_2,\omega,t)S_{V0}(x_1,x_2,\omega) \tag{8}$$

The mean and dynamic lateral (drag) wind forces per unit length of the conductor are calculated as follows based on quasi-steady theory:

$$\bar{f}_D(x,t) = \frac{1}{2}\rho DC_D\bar{V}^2(x,t) \tag{9}$$

$$f_D(x,t) = \rho DC_D\bar{V}(x,t)V(x,t) \tag{10}$$

where ρ is air density; C_D is the static drag coefficient; and D is diameter of the conductor.

The dynamic deformations of the conductor in vertical (cross-wind) and lateral (alongwind) directions, $v_c(x,t)$ and $w_c(x,t)$, are expressed as sum of deterministic time-varying mean component, $\bar{v}(x,t)$ and $\bar{w}(x,t)$, and stochastic dynamic component, $v(x,t)$ and $w(x,t)$, as:

$$v_c(x,t) = \bar{v}(x,t) + v(x,t) \tag{11a}$$

$$w_c(x,t) = \bar{w}(x,t) + w(x,t) \tag{11b}$$

2.2. Analysis of time-varying mean response

It is assumed that the time variation rate of the mean wind speed thus that of the mean drag force is slow compared with the natural frequencies of the conductor. Therefore, the conductor