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# Prediction of wind-induced buffeting response of overhead conductor: Comparison of linear and nonlinear analysis approaches

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ABSTRACT

This study addresses the estimation of buffeting response of overhead conductor based on random vibration theory with closed-form formulations. Special attention is placed on the determination of static deformation with consideration of geometric nonlinearity, and its influence on the dynamic modal properties, aerodynamic modal damping and buffeting response. The dynamic response around the static equilibrium is separated into background and resonant components, which are calculated by using influence function and modal analysis, respectively. The aerodynamic modal damping ratios are estimated in closed-form formulations in which the influence of static swing of the conductor plane is explicitly accounted. Example studies presented in this study illustrate the accuracy and effectiveness of this linear buffeting analysis framework through comparison with nonlinear finite element model (FEM) analysis in the time domain. The importance of consideration of static deformation is revealed for the prediction of alongwind displacement and tension, especially, the resonant response component. The contributions of modal responses to various resonant responses are also examined.

## 1. Introduction

High-voltage power conductors are sensitive to wind excitations. Among various wind-induced responses, the buffeting response of conductors due to wind fluctuations requires a careful study for the design of transmission line systems. A lot of research efforts have been made toward improved understanding and prediction of buffeting response of conductors and the loads transmitted to towers (alongwind reaction or conductor force) under boundary layer wind turbulence. These efforts include analytical predictions, aeroelastic wind tunnel tests, and full-scale measurements (e.g., Davenport, 1979; Matheson and Holmes, 1981; Mehta and Kadaba, 1990; Momomura et al., 1997; Loredo-Souza and Davenport, 1998, 2001, 2002; Battista et al., 2003; Paluch et al., 2007; Cluni et al., 2008; Lin et al., 2012; Hung et al., 2014; Liang et al., 2015; Aboshosha et al., 2016). The research findings have been reflected in current design codes and standards (e.g., ASCE 74, 2009).

Concerning the theoretical analysis of wind-induced buffeting response of conductors, Davenport (1979) presented the gust response factor approach based on conventional linear random vibration theory. Matheson and Holmes (1981) carried out a time domain response analysis by solving the differential equations using finite difference method, and compared to those derived from linear random vibration theory. The wind-induced drag force was calculated based on quasi-steady theory where the aerodynamic damping effect was implicitly included. The results revealed the apparent effects of mean swing angle of the conductor on the conductor deflection. On the other hand, it was confirmed that the alongwind support reaction was dominated by background response and the linear random vibration theory without the consideration of swing angle presented quite accurate estimation. Loredo-Souza and Davenport (1998) compared the results of aeroelastic wind tunnel test and theoretical predictions using linear random vibration theory based on quasi-steady drag force model (Davenport, 1995). The results confirmed the dominance of background component in the alongwind support reaction due to large aerodynamic damping. It was also illustrated that the resonant response can also be important when the conductor characteristics and flow conditions lead to lower value of aerodynamic damping.

The response analysis with a nonlinear finite element model (FEM) of the conductor is able to account for the geometric nonlinearity (e.g., Diana et al., 1998; Yasui et al., 1999; Martinelli and Perotti, 2001; Gattulli et al., 2007). The response analysis has to be carried out in the time domain which is computationally demanding. The wind-induced response can be separated into static response under static wind load

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and dynamic response due to wind fluctuations around the static equilibrium. At higher wind speeds, the static deformation and swing of the conductor plane can be very significant, which lead to a considerable change in cable tension force from the initial state under its weight, thus result in changes in system dynamic properties. That necessities a nonlinear analysis procedure for static response analysis, while a linear theory is more convenient when the change in tension is negligible (Pasca et al., 1998; Gattulli et al., 2007). The dynamic response can be represented in terms of a small number of in-plane and out-of-plane modal displacements. The equations of modal displacements are coupled and with a variety of nonlinear terms due to the dynamic tension which involves quadratic terms of deformations based on compatibility condition (e.g., Pasca et al., 1998; Di Paola et al., 2004; Rega, 2004; Gattulli et al., 2007). The quasi-steady force model also introduces linear coupled aerodynamic damping terms (e.g., Gattulli et al., 2007). The solution of coupled nonlinear equations to stochastic wind turbulence also has to be carried out in the time domain but with enhanced computational efficiency as compared to FEM approach.

When the dynamic deformation around the static equilibrium is small, the dynamic tension resulted from dynamic response can be determined from the compatibility condition by retaining only the linear terms. The system is then modeled as a linear system characterized by the dynamic modal properties at the static deformed position. The linear system permits use of spectral analysis approach for dynamic response analysis. This study examines the effectiveness of this linear approach with closed-form solutions for buffeting response of conductor through its comparison with nonlinear FEM analysis in the time domain. Special attention is placed on the determination of static deformation considering the geometric nonlinearity, and its influence on the dynamic modal properties, aerodynamic modal damping and buffeting response. The dynamic response around the static equilibrium is separated into background and resonant components, which are estimated using influence function and modal analysis, respectively. The aerodynamic modal damping ratios are estimated in closed-form formulations based on quasi-steady theory in which the influence of static swing of the conductor plane is explicitly included. Example studies presented in this study illustrate the accuracy and effectiveness of linear buffeting analysis framework. The importance of consideration of static deformation is revealed for the prediction of alongwind displacement and tension, especially, the resonant response component. The contributions of modal responses to various resonant responses are also examined.

## 2. Analytical framework

### 2.1. Static response analysis

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

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

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

The mean wind speed is perpendicular to the conductor, which is considered as the most unfavorable wind direction for wind-induced response. The mean drag force per unit length of the conductor is

$$\bar{f}_D = \frac{1}{2}\rho\bar{V}^2DC_D \tag{3}$$

where $\rho$ is air density; $\bar{V}$ is the mean wind speed, which is approximately taken as the wind speed at the reference height, i.e., $2/3d_0$ below the supported level, and is considered uniform along the conductor span; $C_D$ is the static drag coefficient; and $D$ is diameter of the conductor.

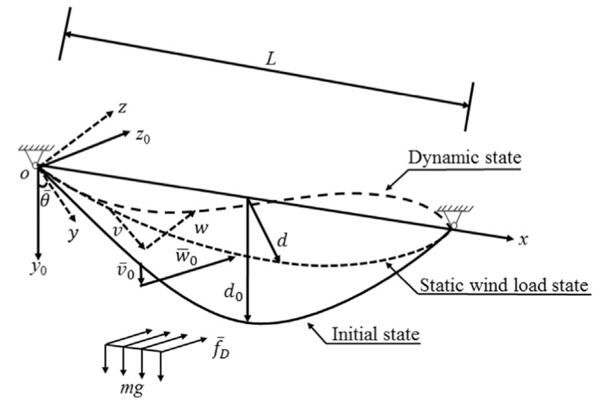


**Fig. 1.** Cable profiles under weight and wind load.

Under the static wind load, the line profile $y_0(x)$ changes to the new static equilibrium state $y(x)$ with the alongwind (horizontal) and crosswind (vertical) static displacements $\bar{w}_0(x)$ and $\bar{v}_0(x)$ respectively, as shown in Fig. 1. The longitudinal tension and sag are denoted as $H$ and $d$. The nonlinear coupled equations of motion of the system under both static wind load and weight are expressed as (Irvine, 1981):

$$H\frac{d^2(y_0+\bar{v}_0)}{dx^2} = -mg \tag{4}$$

$$H\frac{d^2\bar{w}_0}{dx^2} = -\bar{f}_D \tag{5}$$

The compatibility condition of the conductor leads to

$$\frac{(H-H_0)L_e}{EA} = \int_0^L\left(\frac{d\bar{u}_0}{dx} + \frac{dy_0}{dx}\frac{d\bar{v}_0}{dx} + \frac{1}{2}\left(\frac{d\bar{v}_0}{dx}\right)^2 + \frac{1}{2}\left(\frac{d\bar{w}_0}{dx}\right)^2\right)dx \tag{6}$$

where $\bar{u}_0$ is the static displacement along span-wise direction; $E$ is Young's modulus; $A$ is the area of the cable; $L_e$ is a virtual length of the cable defined by

$$L_e = \int_0^L\left(1+\left(\frac{dy_0}{dx}\right)^2\right)^{3/2}dx \approx L \tag{7}$$

The solutions of Eqs. (4) and (5) lead to

$$\bar{v}_0(x) = \frac{(H_0-H)}{H}\frac{mg}{2H_0}x(L-x) \tag{8}$$

$$\bar{w}_0(x) = \frac{\bar{f}_D}{2H}x(L-x) \tag{9}$$

Clearly, the new profile $y(x)$ also follows a parabola:

$$y(x) = \sqrt{(y_0(x)+\bar{v}_0(x))^2 + \bar{w}_0{}^2(x)} = \frac{q}{2H}x(L-x) \tag{10}$$

where $q=\sqrt{(mg)^2+(\bar{f}_D)^2}$ is the total uniform load, and the sag is $d = qL^2/8H$.

The swing angle of the conductor plane is determined as

$$\bar{\theta} = \arctan\left(\frac{\bar{w}_0}{y_0+\bar{v}_0}\right) = \arctan\left(\frac{\bar{f}_D}{mg}\right) \tag{11}$$

Eq. (6) can be represented as

$$\frac{(H-H_0)L}{EA} = \frac{mg}{H_0}\int_0^L\bar{v}_0dx + \int_0^L\frac{1}{2}\left(\frac{d\bar{v}_0}{dx}\right)^2dx + \frac{1}{2}\int_0^L\left(\frac{d\bar{w}_0}{dx}\right)^2dx \tag{12}$$