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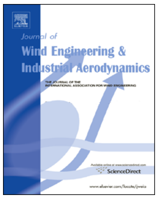

Experimental and numerical study on the responses of a transmission tower to skew incident winds

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ABSTRACT

A study on a lattice suspension tower in a four-span transmission line system subjected to skew incident wind forces is presented via experimental and numerical approaches. The purpose of this work is to investigate the response features of the tower especially to the wind not incoming along the structure's principle axes. At the geometric scaling of 1:80, the aeroelastic model is manufactured with scaled rigidity, mass, area projection and frequency. Wind tunnel tests on the model, with and without conductors, are conducted at a variety of incident angles. Then numerical simulations are applied quasi-steadily to figure out an analytical way of interpreting and supplementing experimental results. Such quasi-steady method is generally valid since the tested aerodynamic damping ratios, though scattered, roughly meet the quasi-steady formulae. Results show that for the tower without conductors the dynamic accelerations do not vary significantly with the incident angle either in the r.m.s. values or in the spectral contents, as wind forces on the tower lend dependency on both the along wind and the across wind components of fluctuating winds thus have equivalent magnitudes at different wind incidences. For the tower with conductors, the longitudinal forces on the conductor are quite different from the lateral ones according to the simulated mechanism. As the co-effect of the additional loads and extra damping provided by conductors, dynamic accelerations of the tower show distinct characteristics in different axes and at different wind incidences.

1. Introduction

The basic structural utilities in an overhead electrical power transmitting line include conductors, shield wires, insulator strings and supporting towers. Conductors are responsible for transmitting the electricity and they are attached to towers using insulator strings. Shield wires protect the line from lightning strike. For the purpose of changing forward direction or preventing continuous collapse, usually a strain tower will be set every several spans to resist tension in the conductors. Thus two adjacent strain towers, intermediate suspension towers and conductors form a relatively independent section which can bear longitudinal, lateral and vertical loads in operation stage, namely Transmission Line System (TLS).

Structural design of TLS usually treats towers and conductors separately and take conductors' wind loading as nodal force exerting on the joint points. Consequently, earlier studies concentrated on towers or conductors respectively.

Based on a few assumptions and quasi-static theory, GRF method was imported into the expression of tower responses (Holmes, 1994). Then mean, background fluctuating and resonant components of wind loads for freestanding lattice towers were deduced and combined for equivalent static load distribution (Holmes, 1996b). Apart from theoretical research, experiments (e.g. Harikrishna et al., 1999) and field measurements (e.g. Bai et al., 2012) were carried out to study dynamic characteristics and wind-induced vibrations of single tower.

As regards to conductors, Davenport (1979) developed an analytical model to predict conductor response in extreme winds. Multiple wind tunnel tests (Shan, 1993, 1994; Loredo-Souza and Davenport, 1998, 2002) on various conductors subjected to turbulent synoptic wind were carried out to investigate the dynamic tension responses.

With progressive comprehension of tower-conductor interaction and rapid development of wind tunnel test technique, aeroelastic TLS tests (Deng et al., 2003; Zhao et al., 2009; Xie and Yang, 2013) were conducted adopting conductor modelling approach presented by Loredo-Souza and Davenport (2001). Similar to field measurements (e.g. Momomura et al., 1997), test results revealed

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Nomenclature

a	mass coefficient of Rayleigh model
a'	coefficient of additional damping
A_i	area projection of ith section
b	stiffness coefficient of Rayleigh model
$\mathbf{C}_{damper}$	damping matrix contributed by additional dampers
C_D	drag coefficient
C_L	lift coefficient
d	diameter of conductor and shield wire
D_i	drag force
f	frequency in Hz
F^*_{xn}, F^*_{yn}	nth generalized wind forces in x and y axes
i	ith section
$\mathbf{K}$	stiffness matrix
L_i	lift force
$\overline{m}$	mass per unit length
$\mathbf{M}$	mass matrix
M^*_{xn}, M^*_{yn}	nth generalized mass in x and y axes
$\dot{q}_{xn}$, $\dot{q}_{yn}$	nth generalized vibration speed in x and y axes
s_0	sag of conductor and shield wire
$\dot{s}_i$	vibration speed
$\bar{U}_i$	mean wind speed
u'_i	along wind fluctuating wind speed
U_i	instantaneous wind speed
U_{Ri}	relative wind speed of U_i against $\dot{s}_i$
$\vec{U}_{Pi}$	projective vector of U_{Ri} on conductors
$\vec{U}_{Ni}$	normal vector of U_{Ri} against conductors
U_{Pxi}, U_{Pyi}, U_{Pzi}	component of U_{Pi} in x, y and z axes
U_{Nxi}, U_{Nyi}, U_{Nzi}	component of U_{Ni} in x, y and z axes
v'_i	across wind fluctuating wind speed
$\dot{x}_i$	vibration speed in x direction
$\dot{y}_i$	vibration speed in y direction
z_R	reference height
z_0	roughness length
α_N	angle between U_{Ri} and U_{Ni}
β_i	angle between U_i and y axis
$\bar{\beta}_i$	angle between $\bar{U}_i$ and y axis
β_{Ri}	angle between U_{Ri} and y axis
γ_0	adjustment factor for span scaling
γ_i	angle between U_i and $\dot{s}_i$
θ_i	angle between $\dot{s}_i$ and x axis
κ	empirical factor
ρ	air density
ω_{xn}, ω_{yn}	nth circular natural frequency in x and y axes
ϕ_{xni}, ϕ_{yni}	nth mode shape coefficients in x and y axes
ζ	damping ratio
ζ_{axn}, ζ_{ayn}	nth aerodynamic damping ratios of the tower in x and y axes

that conductors have significant influences on wind-induced vibration of towers. Moreover, aerodynamic damping,which explains fluid-solid coupling between wind and structures, was much more investigated and theoretical models were proposed (Holmes, 1996a; Kareem and Gurley, 1996; Macdonald and Larose, 2006; Takeuchi et al., 2010; Raeesi et al., 2013).

Due to difficulties in manufacturing aeroelastic models and high cost in carrying out TLS wind tunnel tests, finite element modelling method developed as an important assistant approach. To accurately simulate TLS' dynamic characteristics, many simplified models were presented, including continuous cable model (Irvine, 1981), spatial truss model (Al-Bremani and Kitipornchai, 1992), model consisting of coupled pendulum model in high frequency regime and multi-mass model in low frequency regime (Ozono and Maeda, 1992) and truss model (Yasui et al., 1999) etc.

Because of the large scale, e.g., several kilometers, in span direction of TLS, the situation that fluctuating wind incomes normal to the conductors is the primary concern in previous researches and engineering practice. However, some wind tunnel tests (Lou et al., 1999; Guo et al., 2007; Li et al., 2008, 2011; Xie et al., 2011; Deng et al., 2013; Liang et al., 2015) and on-site measurements (Ballio et al., 1992; Glanville and Kwok, 1995; Moschas and Stiros, 2014) revealed that the across wind responses, compared to the along wind ones, would be of the same order of magnitude. Accordingly, investigators argued that it is necessary to take account of the combination of responses in both directions. Besides, the transmission lines are usually exposed to skew incident winds. Wind tunnel tests conducted by Xie et al. (2013) suggested that the largest acceleration responses of TLS occurred at both 60° and 90° incident angle (relative to the span direction). Similar findings were delivered by Deng et al. (2010) according to experimental results for an aeroelastic model of lattice tower without conductors. They reported that wind incidence of 15° was the most unfavorable condition for their objective. Moreover, other issues concerning, say, assessment of response surface or reliability estimation of TLS under different wind events, need considerations of oblique wind directions, like Mara and Hong (2013).

As few references can be obtained by the authors from open access, this work focuses on the dynamic responses of lattice tower, with and without conductors, to skew incident winds. A practical method, adopted by design guide (e.g., ASCE, 2010), applies a triangular transformation of the along wind responses. The lattice tower and conductors are assumed to be calculated separately. Gust response factors for tower in principle axes and for conductors in lateral direction are specified. More detailed alternative may take account of three-dimensional wind loads. Since some field monitoring data (e.g., Takeuchi, et al., 2010) and wind tunnel test results (e.g., Duan and Deng, 2014) support the argument that vortex-induced vibrations (VIVs) or self-induced vibrations (SIVs) are not dominant in across wind direction, it seems applicable to model three-dimensional wind loads of lattice tower on the basis of quasi-steady assumption. As to loads on conductors, ESDU (1980) suggested a semi-empirical model for normal and axial aerodynamic forces of an infinite cylinder.

The current work considers the scaled model of a typical section of transmission line including four spans of conductors (see Fig. 1). The tower of interest is a suspension tower located at the middle of the whole section, with relatively low stiffness and large vertical extent compared to strain towers. An identical suspension tower is set at each side of the tower of interest. Thus the conductors are expected to be able to swing in longitudinal and lateral directions. Strain towers are set at ends of the section to restrain rigid body displacement and provide initial tension of the conductors. The scope of this study is limited to synoptic wind events. Wind tunnel tests are conducted on the aeroelastic model in Boundary Layer Wind Tunnel Laboratory TJ3 (BLWTL-TJ3) of Tongji University, and numerical simulations are carried out to study the dynamic responses under three-dimensional wind loads. Section 2 describes the full-scale transmission line system that is modeled. Section 3 describes the procedure of aeroelastic model designing,

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