



Numerical simulation of dynamic response of a long-span bridge to assess its vulnerability to non-synoptic wind



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ABSTRACT

Winds generated by non-synoptic events such as those from tornadoes, microbursts or gust fronts, that are non-stationary or transient in nature and extreme in magnitude, can cause major damage to flexible structures. In this paper, a time-domain method is used to simulate the response of a long-span bridge subject to winds generated by a particular type of non-synoptic wind phenomenon such as a microburst to assess the vulnerability of the bridge to such winds. The self-excited or motion-induced and buffeting or turbulence-induced wind loads on the structure were modeled and simulated by Rational Functions and buffeting indicial functions, respectively. Wind from a translating microburst was simulated using empirical relationships that were derived from measurements of a laboratory-simulated microburst and the bridge response calculated to compare it with those induced by an equivalent straight-line wind that is used for structural design. It is shown that microburst induced structural vibration could be larger or smaller than the vibration induced by straight-line wind of equivalent magnitude depending on the relative size of the microburst with respect to the bridge span.

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1. Introduction

Winds generated by tornadoes, microbursts or gust fronts, that are non-stationary or transient in nature and extreme in magnitude, can cause major damage to flexible structures. These types of winds are often referred as non-synoptic winds. The current design of flexible structures such as a long-span bridge, located in thunderstorm-prone areas outside the hurricane zone, is based on design wind speeds derived from thunderstorms that are straight-line winds of neutral atmospheric-boundary-layer (ABL) type, whereas thunderstorms can occasionally produce tornadoes and microbursts that have different wind characteristics compared to those of the design winds. Currently, civil engineering structures are not designed for non-synoptic winds that are transient in nature, so it is important to examine the vulnerability of these structures to such winds. The classic frequency-domain analysis approach for aeroelastic (motion dependent) loads cannot be used

to investigate time-varying structural behavior in non-stationary wind or transient environment. Recent developments in the prediction of wind loads on flexible structures in time domain [1–13] have made it possible to study the wind-structure interaction problems associated with non-stationary wind events such as a microburst. Microbursts are rare events because only 5% of thunderstorms produce microbursts but it can prove to be dangerous for structures because winds near the ground can reach up to 76 m/s (170 mph, peak gust) which far exceeds the design wind speeds of ~38–54 m/s (85–120 mph, 3-s gust at 10 m height) in geographic regions outside the coastal areas where long-span bridges exist. Further, the velocity and turbulence profiles in a microburst wind are quite different from those of straight-line ABL wind. While this difference has been recognized since the mid-1980s when the well-known field experiments on quantifying microburst winds were carried out by Fujita [14], there is a much better understanding of the microburst wind characteristics now because of the numerous physical and numerical simulations and field measurements that were carried out since the mid-1990s for the purpose of quantifying wind loads on engineering structures [15–26].

In this paper, a time-domain method is used to calculate the dynamic response of a long-span bridge in a typical non-stationary wind environment where winds from a microburst approaching the bridge are simulated. Microbursts of three different sizes,

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Nomenclature

h	vertical displacement	ϕ_{wL}, ϕ_{wM}	buffeting indicial functions
α	torsional displacement	C_L	lift coefficient
m	mass per unit length of the bridge	C_M	moment coefficient
I	mass moment of inertia per unit length of the bridge	w	turbulent velocity in vertical direction
L	aerodynamic lift per unit length	U_m	maximum value in the velocity profile
M	aerodynamic moment per unit length	z	elevation position from the ground
ω	natural frequency	b	elevation from the ground where $U = U_m/2$
ζ	critical damping ratio	V_j	jet velocity of the microburst
h_i	vertical displacement of i th mode	D	diameter of the microburst
α_i	torsional displacement of i th mode	H_{il}	(i, l) component of the matrix H
ξ_i	i th eigen – function of vertical displacement	θ_{il}	complex angle of H_{il}
η_i	i th eigen – function of torsional displacement	ϕ_{ik}	random phase angle from its unit uniform distribution between 0 and 2π
l	span of the bridge	S	power spectral density matrix of $u(t)$
ρ	air density	u^*	shear velocity
U	mean wind speed, m/s	z_0	roughness length
B	width of the bridge deck		
A_0, A_1, E, λ	Rational Function Coefficients		
s	non-dimensional time		

relative to the bridge span, are considered and winds resulting from the simulated microburst events are used to generate the wind loads applied on the bridge and its response calculated for comparison with that of a straight-line wind event of equivalent wind speed. The procedure presented here can be used to analyze flexible structures subject to other types of non-synoptic winds.

In time-domain analysis, a very important part is the proper formulation of time-domain aeroelastic loads. Self-excited wind loads in time domain are formulated by indicial functions [3,9] or by Rational Functions that were originally expressed in Laplace Domain [27,28]. There are methods developed recently to indirectly identify indicial functions [9] or directly extract Rational Functions [29,30] through wind tunnel tests. For the calculation of buffeting or turbulence-induced wind loads, frequency-domain admittance functions [31] or equivalent buffeting indicial functions in time domain are used. The buffeting indicial functions can be identified indirectly from the admittance functions that in turn are identified using a technique developed and described in [11], where a section model of the structure is subjected to wind of sinusoidal form at a fixed frequency and repeating this test at several reduced or normalized frequencies by varying the wind speed and/or sinusoidal-gust frequency. Cao and Sarkar [13] performed a validation study for time-domain formulation, in which self-excited and buffeting wind loads on a bridge deck were predicted using Rational Functions and buffeting indicial functions, respectively, and compared with experimentally measured wind loads in stationary and non-stationary (ramp-down) gusty winds. The results from this study were quite encouraging which confirms the feasibility of time-domain formulations in predicting aeroelastic wind loads for non-stationary wind environment.

Here, in this paper, a microburst is simulated to approach the main-span of a long-span bridge such that the center of the microburst translates along the centerline of the main-span perpendicular to the bridge axis. This situation is assumed to produce the most extreme wind distribution along the span of the bridge. The bridge deck is assumed to be streamlined and all of its aeroelastic parameters used in the current simulation are extracted from earlier wind tunnel tests [30]. The main span of the bridge that is dynamically excited here is 1200 m whereas the diameter of the microburst (D) varies as 600 m, 1200 m and 1800 m, to examine the effect of the microburst size relative to the bridge span. The initial position of the microburst center is $1.5D$ from the bridge axis, and it translates by a distance D to a position of

$0.5D$ from the bridge axis. The translation speed of the microburst is set as 20 m/s, which is a typical translation speed for thunderstorms. The microburst winds are simulated on the basis of results of a steady impinging jet of nozzle diameter D and mean jet velocity V_j impinging on a horizontal surface representing a relatively smooth terrain [22]. Further, a straight-line wind case, corresponding to a typical ABL velocity profile over water, is also considered to compare with all the microburst cases. The mean wind speed of the straight-line wind is arbitrarily set at a high value of 60 m/s (134 mph) at the mean height of the bridge deck which is comparable to the extreme case of a microburst. To ensure that the microburst cases are comparable with the straight-line wind case, the mean value of the microburst wind speed time history over the entire translation period sensed at the center of the bridge is set as 60 m/s (134 mph) by adjusting the jet velocity V_j of the microburst. The velocities normal to the bridge axis at other locations of the bridge were below this speed because of the radial nature of the outflow of the microburst.

2. Methods and equations of motion

2.1. Equations of motion

For the long-span bridge discussed here in this paper, a suspension bridge with a streamlined cross-section, the along-wind or lateral degree-of-freedom is less important than the vertical and torsional ones and hence not considered. Only the vertical-torsional modes are used in the current analysis and because the cross-section of the bridge deck used here is streamlined the wind load induced by vortex shedding is neglected. The equations of motion for the bridge can be written as Eqs. (1) and (2).

$$m\ddot{h} + c_h\dot{h} + k_h h = L_{se} + L_b \quad (1)$$

$$I\ddot{\alpha} + c_\alpha\dot{\alpha} + k_\alpha \alpha = M_{se} + M_b \quad (2)$$

where m and I are mass and mass moment of inertia per unit length of the structure, h and α are vertical and torsional displacements of the structure as a function of both time (t) and spanwise position (x), $(\dot{})$ and $(\ddot{})$ are corresponding velocity and acceleration, respectively, L and M are dynamic lift and moment per unit length applied on the structure, c and k are damping coefficient and stiffness of corresponding degree-of-freedom, and the subscripts b and se stand for buffeting load and self-excited load, respectively. Using modal

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