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Wind-induced performance of long-span bridge with modified cross-section profiles by stochastic traffic

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ABSTRACT

The presence of traffic on a slender long-span bridge (SLB) deck has two types of primary impacts: (1) modification of the bridge cross-section profiles, which may influence the flutter derivatives and in turn, wind-induced aeroelastic loads acting on the bridge and (2) additional dynamic loads acting on the bridge including dynamic interactions from the vehicles. As compared to the investigations on the impact of traffic as external dynamic loads, those on the impact from the modification of bridge cross-section profiles are rather rare. A scaled bridge section model with vehicle models distributed on the bridge deck has been tested in the wind tunnel laboratory following the simulated stochastic traffic flow. With the flutter derivatives obtained from the wind tunnel experiments of various modified bridge cross-section profiles by traffic, the present study is to numerically evaluate the impact on the wind-induced performance of the long-span bridge, such as the aeroelastic performance, buffeting response and potential fatigue accumulation.

1. Introduction

The significance of aeroelastic effect of wind on slender long-span bridges was not well recognized until the collapse of the Tacoma Narrows Bridge in 1940, which triggered the continuous progress of bridge aerodynamics in the following half century. Dependent on the specific profiles of the bridge cross-sections, the flutter derivatives (FDs) were proposed by Scanlan and Tomko [11] to characterize the aeroelastic effects of wind. After the FDs are identified from wind tunnel experiments, the wind-induced aeroelastic (or self-excited) forces acting on a long-span bridge can be quantified [12]. With the increase of wind speeds, the aeroelastic effects can become very strong, which may eventually cause divergent dynamic response and the collapse of the whole bridge, namely "flutter instability". In addition, excessive response of the bridge under the excitation of wind turbulence (buffeting) as well as traffic may also result in fatigue accumulation or damages of local bridge members. In contrast to flutter stability which is more of an instantaneous safety concern, the cyclic response of the bridge induced by wind turbulence and traffic over time is more a long-term safety and serviceability issue. For both flutter stability and buffeting response subjected to bridge/traffic/wind interaction, the FDs obtained from wind tunnel tests are the most critical pieces of information.

In traditional flutter and buffeting analyses, traffic was typically ignored in both wind tunnel tests to identify wind coefficients and the numerical predictions [8,12,7,2,1,4]. It is obvious that the approximation of ignoring the presence of traffic on bridge decks, if reasonable, can bring considerable convenience into the study of long-span bridges. Due to the typical adoption of a uniform profile of the cross-sections along a long-span bridge, the FDs identified from a representative segment of a bridge girder can be easily applied to all other segments of the whole bridge as long as the traffic can be ignored. However, if the traffic is realistically considered, the profiles (shapes) of the bridge cross-sections will be modified constantly due to the moving traffic flow. As a result, the modified profiles of the cross-sections are essentially different from location to location along the bridge even at the same time due to the stochastic and moving nature of the traffic flow. Furthermore, the modified profiles of the cross-sections at the same location also vary over different time instants. Therefore, it becomes crucial to investigate whether the common approximation of ignoring the modification of the bridge cross-section profiles due to the presence of traffic is reasonable or not.

Chen et al. [5] carried out a series of bridge section wind tunnel experiments to investigate the impact of stochastic traffic on the flutter derivatives (FDs) of the cross-sections with the modified profiles by stochastic traffic. With the FDs obtained from the wind tunnel experimental study, the present study is to numerically

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evaluate the impact on the wind-induced performance of the long-span bridge with the modified FDs. Specifically, the impacts on the aeroelastic performance, buffeting response and potential fatigue accumulation will all be evaluated. In addition, since most long-span bridges adopt streamlined girders, the main purpose of this study is to investigate the impact of the traffic on the aerodynamic properties of a typical streamlined cross-section for long-span bridges. The study is conducted by making comparisons between the results from the modal analysis as well as the dynamic response prediction using the baseline flutter derivatives (FDs) obtained from the bridge section model tests without any traffic and those FDs obtained from the bridge section model tests with the presence of traffic.

2. Analytical background of bridge/traffic/wind system

2.1. Coupled system with EDWL

In the previous studies conducted by the writers, the methodology of bridge dynamic analysis considering dynamic interactions have been developed [3,4] and based on which, the reliability-based fatigue analysis was also recently conducted [14]. The bridge/traffic/wind interaction analysis model, which will be used in the present study, is briefly introduced [3,4]

$$\mathbf{M_b}\{\ddot{\gamma}_\mathbf{b}\} + \mathbf{C^s_b}\{\dot{\gamma}_\mathbf{b}\} + \mathbf{K^s_b}\{\gamma_\mathbf{b}\} = \{\mathbf{F}\}^\mathbf{b}_\mathbf{w} + \{\mathbf{F}\}^{wheel}_{EQ} \tag{1}$$

where $\boldsymbol{\gamma}_\mathbf{b}$ is the generalized displacement vector of the bridge. $\mathbf{M_b}$ denotes the generalized mass matrix of the bridge. $\mathbf{C^s_b}$ and $\mathbf{K^s_b}$ are the generalized damping and stiffness matrices of the bridge which have included the wind-induced aeroelastic damping and stiffness components for slender long-span bridges, respectively. $\{\mathbf{F}\}^b_w$ is the generalized wind-induced buffeting forces acting on the bridge. $\{\mathbf{F}\}^{wheel}_{EQ}$ is the equivalent dynamic wheel loadings (EDWL) which is both time- and spatially-variant and can be defined as [3]:

$$\{\mathbf{F(t)}\}^{wheel}_{EQ} = \sum_{j=1}^{n_v}\left\{(1-R_j(t))G_j\cdot\sum_{k=1}^{n}[h_k x_j(t)+\alpha_k x_j(t)d_j(t)]\right\} \tag{2}$$

where $R_j(t)$ and G_j are the equivalent dynamic wheel loading ratio and the gravitational force for the jth vehicle on the bridge. n_v is the total number of vehicles on the bridge. n is the total number of modes used of bridge. h_k and α_k are the vertical and torsion mode shapes of the kth mode, respectively. $x_j(t)$ and $d_j(t)$ define the longitudinal and transverse locations of the jth vehicle on the bridge at time t, respectively.

The dynamic analysis procedure using Eq. (1) has following four steps [4]: (1) With the EDWL approach [3], an EDWL database is developed to obtain $R_j(t)$ for each type of vehicle, under each combination of typical wind and vehicle driving speeds through the bridge/wind/single–vehicle interaction analysis; (2) the stochastic traffic flow through the bridge is simulated with the Cellular Automaton (CA) traffic model to obtain the instantaneous speed, and the location of each vehicle on the bridge at each time instant t; (3) to calculate the collective equivalent dynamic forces through Eq. (2) by combining the information offered by the CA simulated traffic flow and the corresponding $R_j(t)$ from the database; and (4) solving the displacement and stress of the bridge through Eq. (1).

Table 2
Properties of tested bridge section model.

Parameter	Label	Value	Unit
Length	L	1.729	m
Width	B	0.778	m
Height	H	0.137	m
Mass moment of inertia/unit length	I_m	0.764	kg m^2/m
1st Bending frequency	f_v	3.68	Hz
1st Torsional frequency	f_α	7.01	Hz
Mass/unit length	M	11.511	kg/m
Measured damping ratio (vertical)	ζ_v	0.00585	/
Measured damping ratio (torsion)	ζ_α	0.00827	/

2.2. State-space based modal analysis

With the modified FDs updated in the stiffness and damping matrices in Eq. (1), the flutter stability can be assessed based on the modal-based analysis of the free vibration system in the state-space format by making the right-hand side of Eq. (1) equal to zero [2]:

$$\mathbf{A\dot{Y}} + \mathbf{BY} = \{\mathbf{0}\} \tag{3}$$

where $\mathbf{A} = \begin{bmatrix}\mathbf{I} & \mathbf{0}\\ \mathbf{0} & \mathbf{I}\end{bmatrix}$, $\mathbf{B} = \begin{bmatrix}\mathbf{0} & -\mathbf{I}\\ \mathbf{K^s_b} & \mathbf{C^s_b}\end{bmatrix}$, $\mathbf{Y} = \begin{Bmatrix}\gamma\\ \dot{\gamma}\end{Bmatrix}$, I is the unit matrix and others were defined in Eq. (1). Rather than identifying the critical flutter wind speed (i.e. under which flutter occurs), the present study will focus on looking into the evolution of the modal properties due to the aeroelastic effect and the potential impact on flutter stability [2]. The focus will be on the wind speeds up to 50 m/s, above which the traffic volume is believed to considerably reduce because of strong wind.

2.3. Dynamic response and fatigue accumulation

With the dynamic response of the bridge being assessed with Eq. (1), the safety and serviceability performance of the bridge can be evaluated through the maximum stress and the fatigue damage index, respectively [4,14]. There are several measures to quantify the fatigue damage such as the life fraction and crack length. [13]. In the present study, the commonly used “fatigue damage index” which is defined as the fraction of life for the bridge member under repetitive stress cycles is adopted to evaluate the fatigue damage [14].

Table 1
Traffic scenarios of wind tunnel tests.

Scenario	Bridge segment	Traffic presence				
Bridge-only	Yes	N/A				
Spatially-continuous traffic scenario	Yes	Moderate flow	Case name	S2.1	S2.2	S2.3
			Occurrence probability	0.055%	0.014%	0.014%
		Congested flow	Case name	S3.1	S3.2	S3.3
			Occurrence probability	0.015%	0.004%	0.004%
Time-continuous traffic scenario	Yes	Moderate flow	Case name	T2.1	T2.2	T2.3
			Time instant	60 s	65 s	70 s
		Congested flow	Case name	T3.1	T3.2	T3.3
			Time instant	60 s	65 s	70 s
Extreme scenario	Yes	Bumper-to-bumper	Case name	Windward side	Leeward side	Both sides