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# Nonlinear aerodynamic and energy input properties of a twin-box girder bridge deck section

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## HIGHLIGHTS

- Motion amplitude-dependent nonlinear aeroelastic properties of a twin-box girder is investigated.
- A critical amplitude is found to cause to flow pattern fully detached.
- Hysteresis loops of dynamic load coefficients are presented.
- Energy trapping properties are obtained in terms of dimensionless coefficients.
- Energy properties show that flutter instability necessitate motion coupling between vertical and torsional motions, and that the symmetricity of the two motions has be identical.

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## ABSTRACT

By means of computational fluid dynamics (CFD), the nonlinear aeroelastic properties of a bridge deck configuration is investigated in this study in terms of amplitude-dependent flutter derivatives and indicial functions. The results are partially compared with experimental results. It shows that the concerned properties exhibit significant dependence on the motion amplitudes. Moreover, based on flutter derivatives, the nonlinear aerodynamic properties can be divided into two groups: the group with torsional amplitudes less or equal than 10°, and the one with amplitudes larger than 10°. Flow patterns around the section of the two groups differ substantially; one group remains an overall streamlined pattern with locally distributed vortices and detached flow, while the other shows fully detached flow with large vortices emerging and developing drastically. Dynamic load coefficients indicate that, as the motion amplitude increases, the smoothness of the hysteresis loops decreases, suggesting irregular fluctuations of the loads resulted from signature turbulence, which becomes progressively prominent. Energy trapping properties derived from indicial functions are expressed in terms of dimensionless coefficients, of which the results indicate there is no possibility of single-DOF flutter, and coupling between vertical and torsional motions is necessary for flutter instability. Moreover, by the analysis of the phase angles involved in coupling, it is indicated that symmetricity of vertical motion has to be consistent with that of torsional motion in the event of a coupled flutter.



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## 1. Introduction

Aerodynamic instability of long-span bridges has been investigated extensively in recent decades. The attention of most of the published literatures in this regard, however, has been paid to linear problems, and the aeroelastic stability of bridge spans is usually judged by flutter thresholds in sorts of design codes. Achievements in aeronautical engineering show repeatedly that a wind speed beyond the flutter threshold does not always mean catastrophic collapse of the structure. The post-flutter behaviors have been shown to depend on a combination of material, geometric and aeroelastic nonlinearities, and to be significant to a structure's robustness design. In some situations, as indicated in aeronautical engineering, it is the geometric nonlinearity alone that dictates the evolution of the limit cycle oscillation (LCO) at post-flutter stages. A number of researchers have paid exclusive attention to this kind of contribution ( Tang et al., 1999; Attar et al., 2003; Attar and Dowell, 2005; Shams et al., 2008; Eskandary et al., 2012; etc.).

Many theoretical models have been developed for airfoils to describe nonlinear aerodynamic properties. The models generally involve a semi-empirical model. Tran and Petot (1981) brought forward ONERA model, which has obtained extensive applications to describe dynamic stall of helicopter blades, wind turbines, etc. (Tang and Dowell, 1993, 2004; Sarkar and Bijl, 2008; Stanford and Beran, 2013); Leishman and Beddoes (1986) developed another semi-empirical model for description of dynamic stall, where a fairly elaborate representation of the nonstationary attached flow depending on the Mach number is included. The model of Leishman and Beddoes also has been widely used ( Leishman, 1988; Galvanetto et al., 2008; etc.); More recently, Larsen et al. (2007) put forward another semi-empirical dynamic stall model for wind turbine airfoils. In general, semi-empirical methods involve a dynamic wind angle of attack and a backbone function. A semi-empirical model should be able to reproduce the static values when velocity terms vanish; that means, they degenerate to corresponding backbone functions.

The above mentioned semi-empirical models were developed for airfoils or helicopter rotors; therefore, they are inapplicable to bluff bridge sections where far less regularities can be found for the formation, development, and detachment of the vortices. In the context of bluff bridge deck sections, Diana et al. (2008, 2010) developed a model that could account for nonlinear effects due to frequency and amplitude. The proposed nonlinear model is a polynomial function of a dynamic angle of attack. Based on artificial neural network, Wu and Kareem (2011) proposed a nonparametric model to capture the hysteretic nonlinear behavior of aerodynamic systems. Later, Wu and Kareem (2015) tried another way based on Volterra theory to describe linear and nonlinear aerodynamic effects. The works of Wu and Kareem (2011, 2015) address phenomenological models which leave aside explicit physical meanings. Another phenomenological model, based on nonlinear flutter derivatives, has been exercised more recently by Gao and Zhu (2015) and Ying et al. (2016). The nonlinear flutter derivatives in this method depend on higher odd-order terms of the motions, and the identification of these derivatives are based directly on resulted time histories.

Most of the above mentioned nonlinear models concern two issues. First, they address hysteresis loops of load coefficients, not development of these loops corresponding to different motion amplitudes; second, they address analytical descriptions of these hysteresis loops, which involves identification of a number of model parameters. In post-flutter simulations, however, the primary issue is evolution of the energy trapping/dissipating properties with the motion amplitudes, instead of exact shapes of hysteresis loops. On the other hand, an analytical description of nonlinearities is not always necessary for computations, especially when the description comes from a group of discrete experimental data, since it does not have any advantage over the original data in terms of accuracy. Based on this ideology, the present work deals with a piece-wise linearized method to express straightforwardly the amplitude-dependent energy properties, which does not pay attention to exact shapes of complicated hysteresis loops. It is believed in this work that energy trapping/dissipating properties are sufficient to describe precisely development of structural motions. The nonlinear aerodynamic properties of a deck configuration employed in the Xihoumen suspension bridge is investigated, in terms of amplitude-dependent flutter derivatives, hysteresis loops, indicial functions (IFs) and energy trapping properties, respectively.

## 2. Description of nonlinear aeroelasticity

### 2.1. Energy properties related to an indicial function

Motion-related aerodynamic loads developed on bluff bridge decks have been denoted conventionally in terms of flutter derivatives, obtained from either wind tunnel tests or from CFD simulations. The self-excited aerodynamic lift and torque per unit length under sinusoidal motions are given as (Scanlan, 1993, 2000; Katsuchi et al., 1999):

$$L_{se} = \frac{1}{2}\rho U^2 B\left[KH_1^*\frac{\dot{h}}{U} + KH_2^*\frac{B\dot{\alpha}}{U} + K^2H_3^*\alpha + K^2H_4^*\frac{h}{B}\right], \tag{1}$$

$$M_{se} = \frac{1}{2}\rho U^2 B^2\left[KA_1^*\frac{\dot{h}}{U} + KA_2^*\frac{B\dot{\alpha}}{U} + K^2A_3^*\alpha + K^2A_4^*\frac{h}{B}\right], \tag{2}$$

where $\rho$ = air density; $U$ = wind speed; $B$ = reference width; $K = B\omega/U$ is the reduced frequency; $\omega$ = circular natural frequency; $H_i^*(i = 1\text{–}4)$, $A_i^*(i = 1\text{–}4)$ are flutter derivatives, $h$ and $\alpha$ are the vertical and torsional displacements; $\dot{h}$, $\dot{\alpha}$ are the derivatives of $h$ and $\alpha$ with respect to time $t$, respectively.

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