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A nonlinear convolution scheme to simulate bridge aerodynamics

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ABSTRACT

A linear convolution scheme involving first-order (linear) kernels for linear bridge aerodynamics is first reviewed and the significance of the selection of proper input parameters is emphasized. Following the concept of nonlinear indicial response function, the linear convolution scheme is extended to the nonlinear convolution scheme involving higher-order (nonlinear) kernels for the treatment of nonlinear bridge aerodynamics using a "peeling-an-onion" type procedure. Utilizing an impulse function as input, a comprehensive kernel identification scheme is developed. A numerical example of a long-span suspension bridge is investigated to verify the fidelity of the proposed nonlinear convolution scheme.

1. Introduction

A main source of nonlinearity in bridge aerodynamics results from flow separation around the deck. For streamlined sections like an airfoil, flow separation occurs only in the case of large angles of attack (dynamic stall) or the shock motions in the transonic region (the shock motion itself also induces nonlinearity). For bluff sections like a bridge deck, flow separation is prevalent as the fluid motion around the deck cannot negotiate sudden changes in the deck profile. The resulting nonlinearity can be viewed from four viewpoints: (i) non-proportional relationship between amplitudes of input and output; (ii) single-frequency input exciting multiple frequencies; (iii) amplitude dependence of aerodynamic and aeroelastic forces and (iv) hysteretic behavior of aerodynamic forces versus angles of attack [1]. Nonlinear effects are usually exploited to offer a possible explanation for any differences observed between the linear analysis results and experiments [2] although it is difficult to delineate their relative contributions.

In order to take into account the increasing nonlinear behavior of bridge aerodynamics observed in wind-tunnel tests, several numerical schemes such as the "band superposition" [3], "hybrid" [4], "rheological" [5] and "artificial neural network" [6] have been proposed over the last decade to advance conventional linear analysis framework [7,8]. Generally, these numerical schemes have been unable to represent completely nonlinear bridge aerodynamics [6,9], which limits their utility and calls for a comprehensive nonlinear analysis framework.

The consideration of nonlinearity is usually carried out in the time domain benefitting from its ability to take into account the nonlinear effects readily. In the time domain, the convolution of a linear kernel, e.g., the unit-step response function, is well known as the Duhamel's integral. In this study, the linear convolution scheme concerning first-order kernels for linear analysis of bridge aerodynamics is reviewed together with a selection of proper input variables. Then, it is extended to the nonlinear convolution scheme involving higher-order kernels for nonlinear analysis of bridges under winds based on the concept of nonlinear indicial response function. A nonlinear convolution scheme is represented utilizing a Volterra-type formalism, which ensures convergence of its truncated form. To facilitate this formalism, a comprehensive kernel identification scheme is developed utilizing the impulse function as input. Finally, a numerical example of a long-span suspension bridge with vertical and torsional degrees of freedom is investigated to verify the fidelity of the simulation based on the proposed nonlinear convolution scheme, where the amplitude dependence of kernels is also discussed.

2. Linear convolution scheme

This study focuses on the simulation based on a two-dimensional (2-D) representation of the deck and the strip theory.

2.1. Input information of bridge aerodynamics

The selection of proper input variables for bridge aerodynamics based on convolution integrals is a critical issue. In the case of gust-induced effects, the input information is straightforward, i.e., the gust fluctuations in each degree of freedom. However, in the case of motion-induced effects, the input information is often misunderstood in bridge aerodynamics.

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It is well known that the motion-induced forces on a bridge deck are dependent on the orientation of local coordinate system and the relative motion between the wind and the deck [10]. In order to simplify the analysis, the case of a bridge deck moving in the absence of flow is first investigated (Fig. 1). As shown in Fig. 1, the orientation of local coordinate system (as denoted by the subscript "b") can be represented by the angle θ defined as the pitching angle, which is the angle between the local coordinate abscissa axis x_b and the global coordinate abscissa axis x; while the relative motion between the wind and the deck can be decomposed into the relative translatory motion represented by $\vec{V}$, which is the time derivative of the displacement $\vec{S}$, and the relative rotational motion represented by $\dot{\theta}$ (velocity of angle of pitch). $\vec{V}$ is represented by the velocity magnitude V and velocity direction γ, which is the angle between the velocity direction and the global coordinate abscissa axis x. It is noted that $\alpha = \gamma + \theta$, where α defined as the angle of attack, is the angle between the velocity direction and the local coordinate abscissa axis x_b. As a result, the motion-induced forces on the bridge deck are functions of V, θ, $\dot{\theta}$ and α .

For a bridge deck harmonically oscillating in vertical and torsional degrees of freedom under a stationary uniform wind flow (constant wind velocity), translation direction γ is a constant. For such a case, α and V can be represented by the variable θ and $\dot{h}$, respectively, where h is the vertical translatory displacement of the deck. Hence, the bridge deck motion can be decomposed into $\dot{h}$, θ and $\dot{\theta}$, as shown in Fig. 2, which contribute to the motion-induced forces on the bridge deck. As indicated in Fig. 2, the translatory motion coupled with θ has a negative equivalent that is coupled with $\dot{\theta}$, hence, combination of motions θ and $\dot{\theta}$ presents a pure harmonic rotary oscillation. It should be noted that, for the streamlined cross section, the contributions to the motion-induced forces from the translatory motion $\dot{h}$ and the orientation of the cross section θ are identical since the flow passing by the structure is always attached on the solid surface. Whereas, for the bluff cross section, the contribution from θ becomes complicated due to the flow separation. There is no clear explanation to demonstrate the assumption of an equivalent physical origin for these two contributions to the aeroelastic forces. Besides, as the harmonic oscillation is applied to the deck, the identified contribution of the orientation of the cross section θ in a wind tunnel naturally involves the apparent moment of inertia effects of the rotational motion. Different values of the identified flutter derivatives in the wind tunnel corresponding to the translatory motion $\dot{h}$ and orientation of the cross section θ also indicate that it is necessary to separate their contributions in bridge aerodynamics and to retain both of them as input variables [11].

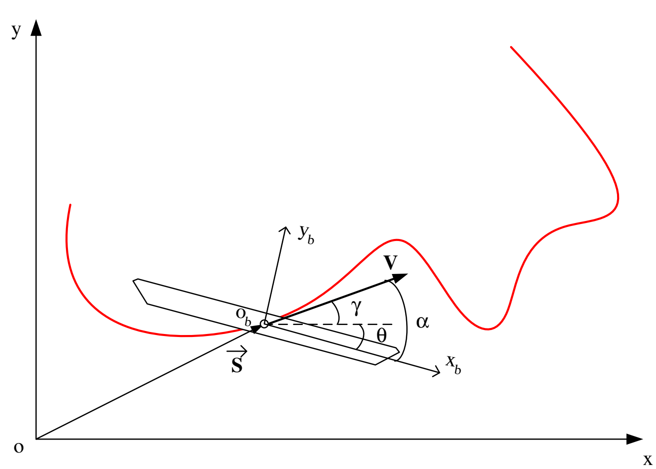

Fig. 1. Arbitrary motion of bridge deck.

2.2. Convolution scheme with indicial response function

With the inclusion of chord-wise correlation, the gust-induced effects (mainly vertical) are directly related to the motion-induced case [12] and are not presented here for the sake of brevity. Generally, the motion-induced forces are expressed as

$$F(t) = f(\theta, \dot{h}, \dot{\theta}, t) \tag{1}$$

where F denotes motion-induced forces, i.e., the motion-induced lift force L or torsional moment M; f represents a general nonlinear function. The linear part of the Taylor expansion of the nonlinear motion-induced lift force increment $\Delta L(t)$ and torsional moment increment $\Delta M(t)$, due to an infinitesimal change in the input variables at time τ, could be represented as [13]

$$\Delta L(t) = -\left[\left\{\left(\frac{\partial L(t,\tau)}{\partial \theta}\right)_{\theta=\theta_0}\left(\frac{d\theta}{d\tau}\Delta\tau\right)\right\} + \left\{\left(\frac{\partial L(t,\tau)}{\partial \dot{h}}\right)_{\dot{h}=\dot{h}_0}\left(\frac{d\dot{h}}{d\tau}\Delta\tau\right)\right\} + \left\{\left(\frac{\partial L(t,\tau)}{\partial \dot{\theta}}\right)_{\dot{\theta}=\dot{\theta}_0}\left(\frac{d\dot{\theta}}{d\tau}\Delta\tau\right)\right\}\right] \tag{2a}$$

$$\Delta M(t) = \left[\left\{\left(\frac{\partial M(t,\tau)}{\partial \theta}\right)_{\theta=\theta_0}\left(\frac{d\theta}{d\tau}\Delta\tau\right)\right\} + \left\{\left(\frac{\partial M(t,\tau)}{\partial \dot{h}}\right)_{\dot{h}=\dot{h}_0}\left(\frac{d\dot{h}}{d\tau}\Delta\tau\right)\right\} + \left\{\left(\frac{\partial M(t,\tau)}{\partial \dot{\theta}}\right)_{\dot{\theta}=\dot{\theta}_0}\left(\frac{d\dot{\theta}}{d\tau}\Delta\tau\right)\right\}\right] \tag{2b}$$

where $\partial y(t,\tau)/\partial x$ ($y = L$, or M and $x = \theta$, $\dot{h}$, or $\dot{\theta}$) denotes the rate of change of $F(t)$ with input at time τ. It is obvious that there are two time scales involved in describing the time dependent characteristics of linear wind–bridge interactions, i.e., the time τ at which the boundary conditions (input variables) change and the time t at which the lift force or torsional moment is measured.

As a time invariant system, the time dependent characteristics of the linear wind–bridge interactions could be described only using one time scale, i.e., the time difference $(t - \tau)$ representing duration since the change in boundary conditions. Hence, as $\Delta\theta$,

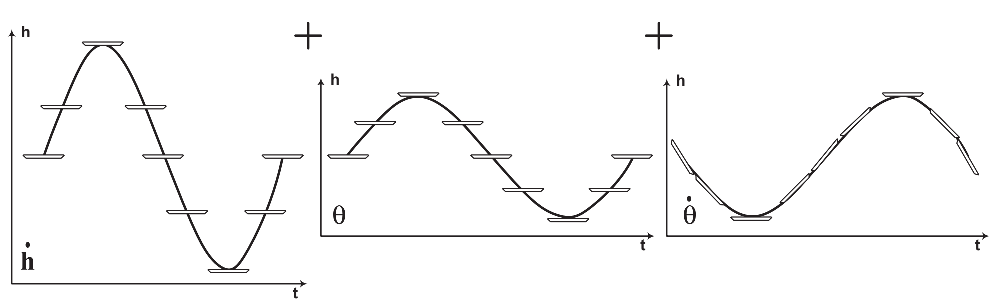

Fig. 2. Decomposition of bridge deck motion.