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A low-dimensional model for nonlinear bluff-body aerodynamics: A peeling-an-onion analogy

Teng Wu [a,b,*], Ahsan Kareem [c]

[a] Department of Civil, Structural and Environmental Engineering, University at Buffalo, State University of New York, Buffalo, NY 14260, United States
[b] State Key Laboratory of Disaster Reduction in Civil Engineering (Tongji University), Shanghai 200092, China
[c] NatHaz Modeling Laboratory, Department of Civil and Environmental Engineering and Earth Sciences, University of Notre Dame, Notre Dame, IN 46556, United States

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ABSTRACT

A low-dimensional model based on the Volterra series is utilized to simulate nonlinear bluff-body aerodynamics. The linear and nonlinear outputs of the aerodynamic system are extracted step by step through a peeling-an-onion analogy. The physical significance of aerodynamic nonlinearities is highlighted during the development of a low-dimensional model. The parameters (kernels) of the low-dimensional model are identified based on impulse functions, which offer a significant computational advantage over the full-order models, e.g., a computational fluid dynamics (CFD)-based scheme. The capability of the proposed low-dimensional model in simulating the nonlinear bluff-body aerodynamic effects is first investigated by three nonlinear examples described by phenomenological models, which represent a gust-induced response, a vortex-induced vibration and a coupling interaction of buffeting and flutter of long-span cable-supported bridges. This is followed by a CFD-based example, representing the motion-induced nonlinear effects on a rectangular bluff body, to further examine and discuss the efficiency and fidelity of the simulation of the low-dimensional model for the nonlinear bluff-body aerodynamics. The Volterra series-based low-dimensional model has shown a remarkable potential for applications to nonlinear bluff-body aerodynamics. The two-dimensional applications discussed in this study could be immediately extended to three-dimensional cases by appropriately accounting for the spanwise correlation of aerodynamic effects.

1. Introduction

Wind-induced effects on structures with bluff cross-sections, governed by the Navier–Stokes equations, are not adequately represented by conventional linear analysis framework established by Davenport (e.g., Davenport (1962)) and Scanlan (e.g., Scanlan and Tomko (1971)). This shortcoming is becoming important for contemporary structures, as their increasing span-lengths and heights make them more sensitive to nonlinear and unsteady aerodynamic/aeroelastic load effects. Significant nonlinear features concerning gust-induced and motion-induced forces on modern bridge decks, observed in wind tunnel studies recently, have placed increasing importance on addressing the nonlinear effects in the design of long-span bridges for wind (Diana et al., 2010; Wu and Kareem, 2013a). It is often believed that nonlinearity usually has favorable effects on the aerodynamic systems due to limit-cycle oscillations. On the other hand, nonlinearity also could result in unfavorable effects on the aerodynamic systems (Dowell and Tang, 2002).

The full-order representation of nonlinear bluff-body aerodynamics needs to recourse to solving nonlinear convected-wave equations of Navier–Stokes model, which involves the order of O(10^6) or more degrees of freedom (Dowell and Hall, 2001). In light of the high computational efficiency and ability to retain essential physics, the low-dimensional models have been rapidly developed in this context over the last several decades (e.g., Dowell and Hall (2001), Silva et al. (2001), Raveh (2001) and Lucia et al. (2004)). For bridge aerodynamics, these models can be employed during the preliminary deck design selection process. Once the design has been finalized one goes to full-blown CFD and/or wind tunnel testing to confirm the estimated behavior or to enhance estimates. There are a number of low-dimensional models which have been successfully applied in engineering, such as the describing function, trajectory piece-wise linearization, artificial neural network (ANN), autoregressive moving average (ARMA), Volterra series and proper orthogonal decomposition (POD). Improvement in the efficiency and robustness of these low-

* Corresponding author. Tel.: +1 716 645 5152; fax: +1 716 645 3133.
E-mail address: tengwu@buffalo.edu (T. Wu).

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dimensional models is a topic of cutting-edge research in aerodynamics community, especially in the aerospace field (e.g., Silva (2005), Amsallem et al. (2012) and Balajewicz et al. (2013)). The essential feature of most of these applications to the aerospace field is that the governing equations of full-order representation are characterized by the inviscid equations (potential or Euler equations). However, for the nonlinear unsteady bluff-body aerodynamics such as the bridge aerodynamics, the more complex Navier–Stokes equation is necessary to be invoked.

In this study, the Volterra series-based model (linear and nonlinear convolutions) is utilized, through a peeling-an-onion analogy, to extract the linear and nonlinear user-defined outputs (forces, pressures, or responses) from the governing equations of the bluff-body aerodynamic system step by step. Volterra series naturally arises from the analysis methods developed to solve the nonlinear ordinary differential equations (ODEs) (Tricomi, 1957). Actually, the implicit operations in terms of the ODEs can be transferred into explicit operations in terms of convolutions (Dowell and Hall, 2001). On the other hand, it is well known that, as the finite-difference scheme with respect to the spatial variables is applied, not only the simplified model of fluid–structure interactions based on potential-flow equations of irrotational flow or with the Euler equations of inviscid flow, but also the full-order model with Navier–Stokes equations of viscid and rotational flow can be degenerated into a set of nonlinear ODEs. As a result, the Volterra series, as a functional series representation, is considered to be naturally appropriate for modeling the nonlinear aerodynamic systems. The Volterra series-based low-dimensional model will be constructed with the impulse-function inputs. As a result, once the parameters (kernels) of the model are identified, it can be employed in predicting the response of the investigated nonlinear aerodynamic system under arbitrary inputs (e.g., harmonic, random, or other signals) (Rugh, 1981). Basically, various aerodynamic and aeroelastic sources which contribute to the wind-induced effects on structures (bridges, buildings, aircrafts, or wind turbines) could be decomposed into perturbations of wind velocities, and translational and torsional motions of the structures. Hence, only three sets of kernels (i.e., gust-related, translational-motion related and torsional-motion related kernels) need to be identified in the simulation of any complex aerodynamic system.

This paper is organized as follows. Section 2 will focus on the development of the low-dimensional model based on Volterra series through a peeling-an-onion analogy, where the physical significance of the nonlinearities in the bluff-body aerodynamics is highlighted. Besides, the truncated Volterra series is discussed to conveniently apply the developed low-dimensional model to weakly nonlinear aerodynamic system. In Section 3, three nonlinear phenomenological examples, which represent the gust-induced response, vortex-induced vibration, and coupling interactions of buffeting and flutter of the long-span cable-supported bridges, respectively, are employed to show the capability of the proposed low-dimensional model in simulating the nonlinear bluff-body aerodynamic effects. In Section 4, a computational fluid dynamics (CFD)-based example, representing the motion-induced nonlinear effects of a rectangular bluff body, is investigated to further discuss the efficiency and fidelity of the simulation of the low-dimensional model for the nonlinear bluff-body aerodynamics.

2. Volterra series based model

2.1. A peeling-an-onion analogy

Nonlinear effects in bluff-body aerodynamics may result from the flow separation, reattachment around the deck, and the three-dimensional wake dynamics. 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 Duhamel's integral. If the response of a general dynamic system due to a unit-step function (unit-step response function or indicial response function) $a(t)$ is known, then the response $y(t)$ of a time invariant, causal, linear system under arbitrary input $x(t)$ can be obtained in the time domain by (e.g., von Kármán and Biot (1940))

$$y(t) = a(t)x(0) + \int_0^t a(t-\tau)\dot{x}(\tau)d\tau \tag{1}$$

where the dot denotes a derivative with respect to time. For the streamlined cross-section, such as the thin airfoil, the unit-step response could be derived theoretically, e.g., the Küssner function (gust input) or Wagner function (motion input). However, for the bluff cross-section, such as the bridge deck, there is no such theoretical unit-step response as the potential flow theory and Kutta condition cannot be applied to bluff-body aerodynamics. A commonly applied approach utilizes the measured transfer functions (aerodynamic admittance functions or flutter derivatives) in wind tunnel to obtain the effective unit-step responses with an indicial function or a rational function approximation scheme (e.g., Scanlan et al. (1974), Bucher and Lin (1988) and Chen and Kareem (2003)). Some other attempts are to directly measure these elementary response functions of bluff cross-sections in wind tunnels (e.g., Caracoglia and Jones (2003)) or to numerically calculate them utilizing CFD technique (e.g., Turbelin and Gibert (2001)).

To capture the nonlinear dynamic features, Tobak and Pearson (1964) considered a more generalized situation where the unit-step response function depended not only on the motion $x(\tau)$ at time τ at which the unit-step input was made, but also on all the past values of x. Hence, the nonlinear dynamic response could be expressed as (Tobak and Pearson, 1964)

$$y(t) = \tilde{a}\{x(0);\ \ t, 0\}x(0) + \int_0^t \tilde{a}\{x(\kappa);\ t, \tau\}\dot{x}(\tau)d\tau \tag{2}$$

where $\tilde{a}(x(\kappa);\ t, \tau)$ denotes the nonlinear indicial (unit-step) response function. The nonlinear unit-step response function is a functional and could be defined by the functional derivative (Fréchet derivative) with respect to the input x. The concept of nonlinear unit-step response function offers a general framework to simulate nonlinear aerodynamics; however, its translation to applications is intractable. To obtain a practical nonlinear analysis framework for real problems, Wu and Kareem (2013b) utilized a "peeling-an-onion" type approach, in which the nonlinear effects of the dynamic system are extracted from a nonlinear unit-step response function using a "step-by-step" procedure. Obviously, if the dynamic system is linear and time-invariant, $\tilde{a}(x(\kappa);\ t, \tau)$ reduces to $a(t-\tau)$, which is characterized by one time scale $(t-\tau)$. Accordingly, the nonlinear unit-step response function could be expressed as

$$\tilde{a}\{x(\kappa);\ t, \tau\} = \left[a(t-\tau) + \int_0^t \tilde{a}^{non}\{x(\kappa);\ t, \tau\}\dot{x}(\kappa_1)d\kappa_1\right] \tag{3}$$

where it is assumed that $x(0)=0$ to provide a parsimonious model. The identification of $a(t-\tau)$ only needs a single step-function input.

It should be noted that there could be infinite time scales in nonlinear unit-step response functions given in Eq. (3) since κ may attain an arbitrary value in the time interval $[0, t]$. In the bluff-body aerodynamics, taking the motion-induced effects as an example, the effects due to multiple time scales may well represent the higher-order (nonlinear) coupling effects of the motion