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Reduced-order modeling and calculation of vortex-induced vibration for large-span bridges

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ABSTRACT

The Volterra theory-based reduced-order modeling (ROM) technique is utilized for simulating fluid-structure interactions of bridge decks during vortex-induced vibration (VIV). To improve the order of nonlinearity adopted in the Volterra series, sparse form kernels are adopted in this study. To illustrate and validate the performance of ROM in simulating fluid-structure interactions of VIV, a real bridge deck is used as a case study. The kernels in the Volterra series are identified using least squares with input–output pairs obtained from a CFD approach. Results indicate that ROM can well reproduce the inherent nature of nonlinearities existing in fluid-structure interactions described by the CFD approach. A method for calculating the VIV of bridges by combining ROM with the structural finite element model is also proposed. The VIV performance of a real bridge is obtained through the proposed method and is compared with field measurements.

1. Introduction

Large-span bridges are quite sensitive to wind effects. Since the collapse of the Tacoma Narrows Bridge, there has been great development in the subject of bridge wind resistance. However, there are still some aspects that need to be further improved, among which is the prediction of vortex-induced vibration (VIV) for a real bridge at the concept design stage.

The most direct way to achieve this object is to conduct wind tunnel experiments on an aeroelastic model that has the same dynamics and configurations as a real bridge, or to use the CFD approach with three-dimensional (3D) grids and arbitrarily shaped moving boundaries. The involving of a real 3D bridge in the CFD approach will be difficult to implement in the foreseeable future. In addition, experimental results of an aeroelastic model can seldom be comparable with those of field measurements or sectional models, since the scale ratio of an aeroelastic model is usually much smaller than that of a sectional model. Thus, wind tunnel experiments or CFD calculations of VIV are normally conducted on a sectional model with structural parameters determined according to the equivalent modal mass of the deck for a certain mode.

However, the VIV response of a structure is sensitive to a structural parameter: the mass-damping parameter. For large-span bridges, there are numerous VIV modes in the velocity range of interest. The modal mass and modal damping vary for each mode, which would require a mountain of experimental work or CFD calculations on sectional models in order to obtain the full VIV performance of a bridge. Furthermore, a real bridge is a flexible structure with 3D modal shapes whose VIV response varies with that of the sectional model. Moreover, oncoming flows are not always uniformly distributed along the span-wise axis of the bridge. In addition, 3D modal shapes may cause vortices to move along the span-wise axis. All these 3D effects of flow fields may cause a loss of coherence of VIV forces along the span-wise direction, and result in inconsistency between the VIV responses of the sectional model and the real bridge.

A promising way to overcome these problems is to utilize mathematical models to model the flow-structure interactions existing in VIV and to combine these models with the structural finite element model to calculate the VIV responses of a bridge under different modal conditions.

Since the work of Bishop and Hassan (1964), a lot of these kinds of models have been proposed, which can be roughly divided into two main categories: single-degree-of-freedom models and two-degree-of-freedom models. Single-degree-of-freedom models can be further classified into negative-damping models (D'Asdia et al., 2003; Ehsan and Scanlan, 1990; Goswami et al., 1993; Larsen, 1995; Marra et al., 2011; Scanlan, 1998) and force-decomposition models (Griffin, 1980; Iwan and Botelho, 1985; Sarpkaya, 1978). Two-degree-of-freedom models can also be further divided into two main subclasses: wake-oscillator models (Facchinetti et al., 2004; Farshidianfar and

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Zanganeh, 2010; Skop and Balasubramanian, 1997) and Milan-oscillator models (Diana et al., 2006; Falco et al., 1999).

The goal of a mathematical model for VIV should be prediction for a certain deck shape for values of mass-damping parameters different from that for which the model parameters were estimated. Unfortunately, none of the above empirical models seem to be able to accomplish this task, since they always have arbitrarily assumed forms that hardly touch the intrinsic nature of fluid-structure interactions.

Recently, some conceptually novel and computationally efficient techniques have been proposed for computing unsteady flows and fluid-induced effects, e.g. reduced order modeling (ROM) techniques. Among the various ROMs, the Volterra theory-based model provides the possibility to catch the inherent nature of nonlinearities and memory effects existing in fluid-structure interactions. The basic premise of this model is that a large class of nonlinear systems can be modeled as a sum of multidimensional convolution integrals of increasing order (Volterra et al., 1959).

The Volterra theory was first proposed and successfully applied in electrical engineering, and was then utilized to model non-Gaussian fluid loadings and mechanical nonlinearities as well as fluid-structure interactions in the fields of offshore engineering (Rugh, 1981; Schetzen, 2006). After that, Silva (1997) applied it in modeling the aeroelastic phenomenon in aerospace engineering. Recently Wu and Kareem introduced it into bridge wind engineering to model aerodynamics and aeroelasticity (Wu and Kareem, 2013a, 2015). Wu and Kareem (2013b) studied the prospect of Volterra series in modeling the VIV system of a bridge. However, the VIV system in their study is represented by the traditional nonlinear semi-empirical model, which is still a far cry from practical application.

In this paper, the Volterra theory-based reduced-order model is applied in practice by involving a real bridge. A procedure for calculating the VIV response of a bridge by combining ROM with the structural finite element model is also proposed. This paper is organized as follows: Section 2 briefly introduces the reduced order modeling of VIV and its kernel identification method; Section 3 applies ROM to a real bridge deck to model the fluid-structure interactions existing in VIV; Section 4 proposes a procedure for calculating the VIV of bridges by combining ROM with the structural finite element method, and the VIV performance of a real bridge is obtained by using this procedure; and Section 5 gives some concluding remarks.

2. Reduced-order modeling and kernel identification

2.1. Reduced-order modeling of bridge deck VIV

For bridge decks submerged in flow fields, as discussed by Wu and Kareem (2013a), motion-induced effects under a stationary uniform wind flow (constant wind velocity) can be uniformly expressed by taking the vertical motion velocity $\dot{y}$ and the rotary motion θ and velocity $\dot{\theta}$ as the input information of bridge aerodynamics:

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

where, f denotes a generalized function. The VIV of a bridge deck often occurs in a single degree of freedom. Taking the vertical degree of freedom as an illustration, the lift force on a strip of deck can be expressed as:

$$F(t) = \frac{1}{2}\rho U^2 D C_L(\dot{y}, t) \tag{2}$$

where, $C_L(\dot{y},t)$ denotes normalized lift forces; D is deck height; U is the oncoming wind velocity; and y is the structural vertical displacement from the static deformation position.

The VIV system can typically be treated as time-invariant, causal and with fading memory. For such a system, the lift force can be uniformly represented as:

$$\begin{aligned} C_L(t) = & \int_0^t h_1(\tau)\dot{y}(t-\tau)d\tau + \int_0^t\int_0^t h_2(\tau_1, \tau_2)\dot{y}(t-\tau_1)\dot{y}(t-\tau_2)d\tau_1 d\tau_2 \\ & + \sum_{p=3}^{M}\int_0^t\cdots\int_0^t\int_0^t h_2(\tau_1, \ldots, \tau_p)\dot{y}(t-\tau_1)\cdots\dot{y}(t-\tau_p)d\tau_1\cdots d\tau_p \end{aligned} \tag{3}$$

where, $h_1(\tau)$ is the first-order kernel, which describes the linear behavior of the system; $h_p(\tau_1, \ldots, \tau_p)$ is the pth-order kernel term, which describes the pth-order nonlinearity existing in the system; and M is the degree of nonlinearity to be considered in the VIV system.

In real practice, the time series of both $\dot{y}(t)$ and $C_L(t)$ generated either from experiments or CFD calculations are discrete time series. Thus, Eq. (3) is always written in discrete-time form, which can be expressed as:

$$\begin{aligned} C_L[k] &= \sum_{p=1}^{M} H_p[k] \\ H_p[k] &= \sum_{m_1=0}^{M_p}\cdots\sum_{m_p=0}^{M_p} h_p[m_1, \ldots, m_p]\prod_{j=1}^{p}\dot{y}[k-m_j] \end{aligned} \tag{4}$$

Eq. (4) can be rewritten in matrix form:

$$\mathbb{CL}_{N\times 1} = \mathbb{Y}'_{N\times Q}\mathbb{H}_{Q\times 1} \tag{5}$$

where $N = n + 1$ denotes the length of the input-output pairs; Q denotes the length of the kernel vector $\mathbb{H}_{Q\times 1}$ in the discrete-time model; $\mathbb{CL}_{N\times 1}$ is a vector of the output data; and $\mathbb{Y}'_{N\times Q}$ is a matrix which consists of the input data combinations.

$$\begin{aligned} \mathbb{CL}_{N\times 1} &= [C_L[0], C_L[1], \ldots, C_L[n]]^T \\ \mathbb{Y}'_{N\times Q} &= \left[Y'^{1}_{N\times Q1}, Y'^{2}_{N\times Q2}, \ldots, Y'^{p}_{N\times Qp}, \ldots, Y'^{M}_{N\times QM}\right] \\ \mathbb{H}_{Q\times 1} &= \left[\mathbb{H}^1_{Q1}, \ldots, \mathbb{H}^p_{Qp}, \ldots, \mathbb{H}^M_{QM}\right]^T \end{aligned} \tag{6}$$

Since the summation notation for the Volterra operators in Eq. (6) can be quite complicated, for illustration purposes, an explicit expression for a particular Volterra series expansion is provided in the Appendix A.

2.2. Kernel identification

The application of the Volterra series in engineering fields can be roughly classified into two main categories. The first is to represent a dynamic phenomenon that has complicated analytical expressions, so the kernels can be generated by using the harmonic probing method. The other is to build a model for an observed dynamic phenomenon that does not have any analytical expression, so the kernels are estimated from experimentally or numerically generated data.

The reduced order modeling of VIV using the Volterra series belongs to the latter case, so experimentally or numerically generated data is needed. Traditionally in aerodynamic and aeroelastic applications, kernel identification has been performed using impulsive inputs. However, the identification of Volterra kernels through impulse-input approach is a resource-intensive endeavor. For kernels that are larger than 3, the analytical details for input-output relations become increasingly fussy, and the interpolation idea involving impulses of various weights becomes increasingly barren from a feasibility viewpoint. Thus, the identification of kernels through impulse-input approach is always limited to the second-order. In fact, recent studies indicate that the impulse identification method is far from optimal in terms of accuracy and efficiency comparing with the least-square approach, especially when higher-order kernels are involved in this process (Balajewicz and Dowell, 2012; Balajewicz et al., 2012).

It is well known that the even-order terms capture the even-order super-harmonics and thus take into account the asymmetric nonlinearities, whereas the odd-order terms capture the odd-order super-harmonics and thus take into account the symmetric nonlinearities.