VOLTERRA SERIES-BASED NONLINEAR BUFFETING ANALYSIS OF LONG-SPAN BRIDGES SUBJECTED TO NON-SYNOPTIC WINDS

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1. INTRODUCTION

Currently, long-span bridges are not designed for non-synoptic winds that are transient in nature, thereby it is important to examine the vulnerability of these flexible and low damping structures. To highlight the effects of non-synoptic winds on bridge aerodynamics, Hu et al. (2013) employed the linear unsteady (LU) wind load model based on the linear convolution theory and the real typhoon wind data to perform the non-stationary buffeting analysis of long-span bridge in a complex terrain. Nevertheless, the effect of aerodynamic nonlinearity on buffeting response was ignored. To the authors' knowledge, such studies are rarely conducted which consider the effects of aerodynamic nonlinearity and non-synoptic winds on buffeting response of long-span bridges. Therefore, a versatile, general and unified nonlinear framework is needed for the accurate prediction of buffeting response of long-span bridges under non-synoptic winds. Recently, the Volterra series has been introduced into structural engineering by Wu and Kareem (2013), which could simulate a nonlinear dynamical system with sufficiently high accuracy. However, this model has not been verified for the real typhoon winds. Moreover, Volterra model has also not been applied to a full-scale real bridge model, which calls into question its capability and versatility.

This paper presents a nonlinear framework for the prediction of buffeting response of long-span bridges subjected to non-synoptic winds by using Volterra series-based wind load model. First, the Volterra kernels are identified by (1) experimental data (2) Artificial Neural Network (ANN). Then, the non-synoptic wind fields are simulated around the bridge based on the evolutionary power spectral density (EPSD) of measured wind speed. Finally, a numerical example of a real bridge model is presented, and buffeting analysis results are compared with the measurement data and LU model.

2. VOLTERRA SERIES-BASED WIND LOAD MODEL

The problem of nonlinear wind-bridge interaction entails a 3D bridge model immersed in a non-synoptic, unsteady and turbulent wind flow which causes the time-varying 3D motion of a bridge structure as shown in Fig. 1. Owing to the complex nature, the wind loads on bridge deck can be decomposed into two time-varying components i.e., static and buffeting including self-excited effects. Eq. (1) shows the time-varying static component (Q_{st}(t)) of wind loads acting on bridge deck with unit length and width B in which ρ is the air density; C_Q denotes the aerodynamic force coefficient which depends on the time-varying mean wind attack angle ($\bar{\alpha}(t)$) and $\overline{U_{tv}}(t)$ is time-varying mean wind speed. In order to formulate the buffeting forces on a bridge deck in time-domain, LU model is usually adopted. To enhance the efficiency of this model, the Volterra series is used in this paper, which introduces all kinds of aerodynamic and aeroelastic nonlinearities into LU model. According to the Volterra series, the output of a continuous, nonlinear time invariant (NLTI) and fading memory system is related to the input signal through the multidimensional infinite convolution integrals of increasing order. Thus, Eq. (2) shows a general expression for the nonlinear and non-synoptic wind-induced buffeting forces on the bridge deck in a discrete form, in which $Q_b[n]$ denotes the buffeting lift force, drag force and pitching moment; ϕ_{Qu} and ϕ_{Qw} denote the first-order kernels; ϕ_{Quu}, ϕ_{Qww} and ϕ_{Quw} are the second-order direct and cross kernels, respectively, and u and w are the longitudinal and vertical wind fluctuations, respectively. It is worth noting here that Eq. (2) will be multiplied by B to compute the pitching moment.

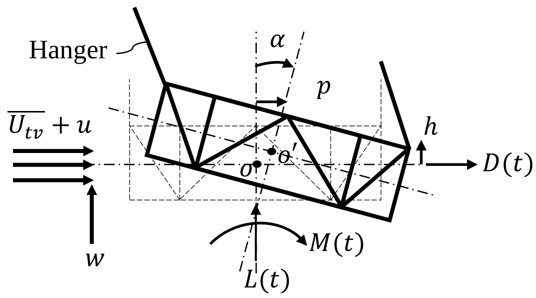

Fig. 1 Motion of bridge deck and wind force components

$$Q_{st}(t)=\frac{1}{2}\rho\overline{U_{tv}}(t)^2BC_Q\big(\bar{\alpha}(t)\big) \tag{1}$$

$$\begin{aligned}Q_b[n]=\frac{1}{2}\rho\overline{U_{tv}}[n]^2B\Bigg[\Bigg\{\left(\frac{2C_Q\phi_{Qu}[0]}{\overline{U_{tv}}[n]}\right)u[n]+\left(\frac{C_Q'\phi_{Qw}[0]}{\overline{U_{tv}}[n]}\right)w[n]\Bigg\}+\Bigg\{\sum_{k=0}^{M}\left(\frac{2C_Q\dot{\phi}_{Qu}[k]}{\overline{U_{tv}}[n]}\right)u[n-k]+\\ \sum_{k=0}^{M}\left(\frac{C_Q'\dot{\phi}_{Qw}[k]}{\overline{U_{tv}}[n]}\right)w[n-k]\Bigg\}+\Bigg\{\sum_{k_1=0}^{M}\sum_{k_2=0}^{M}\left(\frac{2C_Q\dot{\phi}_{Quu}[k_1,k_2]}{\overline{U_{tv}}[n]^2}\right)u[n-k_1]\,u[n-k_2]+\\ \sum_{k_1=0}^{M}\sum_{k_2=0}^{M}\left(\frac{C_Q'\dot{\phi}_{Qww}[k_1,k_2]}{\overline{U_{tv}}[n]^2}\right)w[n-k_1]\,w[n-k_2]+2\sum_{k_1=0}^{M}\sum_{k_2=0}^{M}\left(\frac{C_Q'\,\dot{\phi}_{Quw}[k_1,k_2]}{\overline{U_{tv}}[n]^2}\right)u[n-k_1]\,w[n-k_2]\Bigg\}\Bigg]\end{aligned} \tag{2}$$

Keywords: Buffeting response, Non-synoptic wind, Volterra series, Long-span bridges, Artificial Neural Network
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3. IDENTIFICATION OF VOLTERRA KERNELS

In this paper, Volterra kernels are identified by using two approaches (1) experimental data (2) Artificial Neural Network (ANN). The former method requires the frequency-dependent flutter derivatives of a bridge deck through wind-tunnel test, whereas the latter uses the set of measured inputs and outputs to develop the nonlinear relationship by the associated synaptic weights. Thus, a second-order polynomial function is used since it represents the best fit to the input-output data. Fig. 2 shows the identified second-order Volterra kernels of Akashi-Kaikyo bridge.

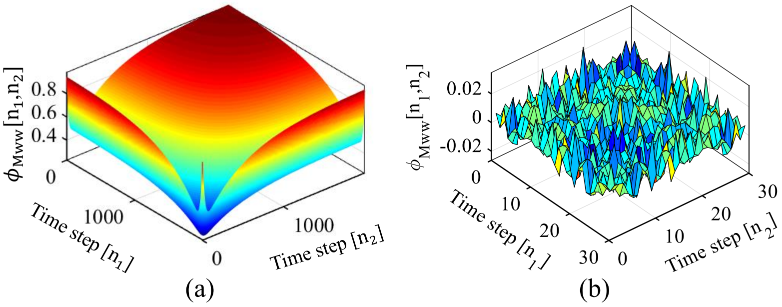

Fig. 2 Second-order Volterra kernels of Akashi-Kaikyo bridge via (a) Flutter Derivatives (FD) (b) Artificial Neural Network (ANN)

4. SIMULATION OF NON-SYNOPTIC WINDS AND NUMERICAL EXAMPLE

The non-synoptic longitudinal wind field is simulated through the unconditional simulation technique based on the assumption that EPSD remains uniform along the bridge length. Herein, EPSD is estimated by using wind speed time history recorded at the center node of main span of Akashi-Kaikyo bridge during typhoon TY9807, whereas the vertical fluctuating wind is simulated as a stationary process by using vertical power spectrum proposed by Von-Karman. The entire deck of the bridge is divided into segments of equal lengths such that each segment receives a 10min record of non-synoptic wind speed time history.

A 3D FE model of Akashi-Kaikyo bridge is developed using the commercial FE package in *ABAQUS* as shown in Fig. 3. The material properties and all characteristics of the elements are determined according to the related design codes and the effect of geometric nonlinearity is also included in the static analysis for the initial balanced state of bridge. The eigenvalue analysis is performed to extract the first fifty eigen-modes, which shows that the first symmetric lateral, vertical and torsional modes occur at 0.04Hz, 0.0645Hz and 0.147Hz, respectively. The wind loads are computed based on both wind models (Volterra FD and Volterra ANN) in two parts i.e., time-varying static and buffeting forces including self-excited effects and applied to the bridge deck. The modal analysis is performed for each wind model by using a 0.5% of critical damping for all modes. The buffeting analysis results of both models at the center node of main span of the bridge are also compared with the displacement measurement and LU model as shown in Fig. 4, which depicts that LU model yields the buffeting response about a constant mean response, whereas Volterra FD and Volterra ANN models simulate the buffeting responses about the time-varying mean response. Moreover, the accuracy of Volterra models over LU model is quantified in terms of mean-squared error (MSE) with respect to measurement response, which shows that Volterra models simulate the buffeting response with high accuracy, confirming the appropriateness of the proposed nonlinear scheme.

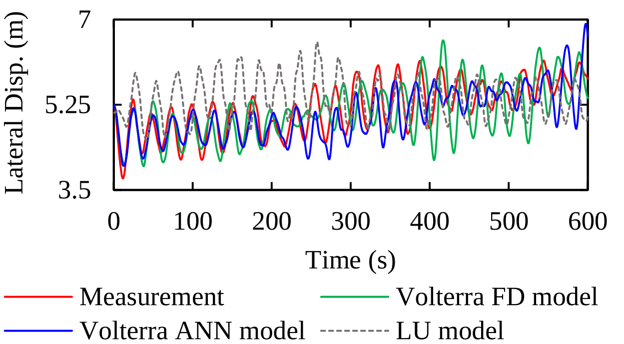

Fig. 4 Comparison between simulated and measured buffeting responses of Akashi-Kaikyo bridge

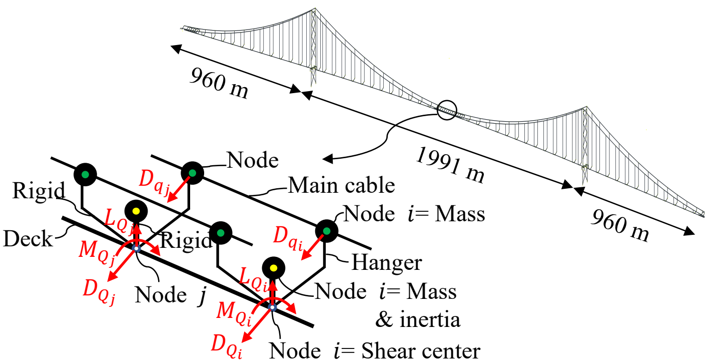

Fig. 3 FE model of Akashi-Kaikyo bridge

5. CONCLUSIONS

A nonlinear framework is proposed in this paper for the prediction of non-synoptic wind-induced buffeting response of long-span bridges in time-domain by using Volterra series-based wind load model. From the analysis results, it is observed that the extension of LU model to Volterra FD and Volterra ANN models can improve the accuracy of predicting the nonlinear buffeting response of bridges. This highlights the paramount importance and usefulness of considering the non-synoptic winds and aerodynamic and aeroelastic nonlinearities in the buffeting analysis of long-span bridges.

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