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Stochastic characterization of wind field characteristics of an arch bridge instrumented with structural health monitoring system

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ABSTRACT

This paper aims to conduct a stochastic characterization of wind field characteristics nearby an arch bridge based on long-term monitoring data from an instrumented structural health monitoring (SHM) system. The fluctuating wind characteristics are first presented by analyzing the real-time wind monitoring data. A genetic algorithm (GA)-based finite mixture modeling approach is proposed to formulate the joint distribution of the wind speed and direction. For the probability density function (PDF) of the wind speed, a two-parameter Weibull distribution is applied, and a von Mises distribution is selected to present the PDF of the wind direction. The parameters of finite mixture models are estimated by the GA-based parameter estimation method. The effectiveness of the proposed direct probabilistic modeling approach is validated by use of one-year of wind monitoring data, and compared with the traditional angular-linear (AL) distribution-based indirect modeling approach in terms of the Akaike's information criterion (AIC), Bayesian information criterion (BIC) and R^2 value. Results indicate that the proposed GA-based finite mixture modeling approach fits the measured data better than the AL distribution-based indirect modeling approach. In addition, the joint distribution of the wind speed and direction will facilitate the wind-resistant design and wind-induced fatigue assessment of long-span bridges.

1. Introduction

With increase in bridge span, bridge structures become more sensitive to the ambient excitations because of their slender and flexible characteristics. Among various types of structural responses caused by external dynamic excitations, wind-induced vibrations may be the primary effect on the serviceability and safety of bridge structures, especially for long-span cable-stayed bridges and suspension bridges [14,7]. A typical example is the collapse of the Tacoma Narrows Bridge in 1940. Therefore, wind loads play a significant role in the design of long-span bridges, and their aerodynamic characteristics have been a focus of attention for structural safety evaluation. As wind characteristics depend on the geographical environment, terrain roughness and structural shape, it is essential to consider these site-dependent features to implement accurate wind-input simulation for bridge aerodynamics research [17,10]. In this regard, to facilitate the wind-resistant design and wind-induced fatigue assessment of long-span bridges, it becomes necessary to analyze the field wind characteristics, mainly involving average wind properties, e.g., average wind speed and direction, as well as the fluctuating wind characteristics, e.g., wind turbulence intensity, gust factor, turbulence integral scale and wind power spectral density (PSD).

As for the stochastic characterization of average wind features, three statistical analysis methods are commonly employed, i.e., the stationary random process method [23], the maximum wind coefficient method [18], and the joint probability distribution method [4]. Amongst them, the joint probability distribution has been a widely used statistical method to calculate the wind power and to evaluate the structural fatigue damage. Feng et al. [6] investigated the joint distribution of wind speed and direction for wind farm power calculation and layout optimization. Gu et al. [9] established the joint probability density function (PDF) of wind speed and direction to estimate the fatigue life of steel girders of the cable-stayed Yangpu Bridge. Xu et al. [24] assessed long-term wind-induced fatigue damage by integration of the joint distribution of wind speed and direction. A significant observation obtained from current research is that the estimated fatigue damage may have serious errors due to the inaccuracy of the derived continuous joint PDF of wind speed and direction [2].

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One major factor which will affect the accuracy of the stochastic characterization of the average wind feature is the source of the wind data. Due to the difficulty in collecting complete wind data near the bridge site, previous investigators usually applied wind data measured by meteorological observatories near bridges. Simiu et al. [19] exploited the wind data routinely collected from major weather stations in the United States and used the probability distribution to fit the largest yearly wind speed data in eight principal compass directions. Torres et al. [20] utilized 10-min mean wind data gathered from eleven meteorological stations distributed in Spain and estimated the Weibull parameters of eight directional sectors. However, there are several disadvantageous aspects, e.g., the sampling frequency is set to be 10-min or one day in the meteorological stations, the wind data are recorded with sixteen orientation angles instead of random angles, and the meteorological stations are usually far from the bridge site and thus the wind data obtained from the meteorological stations cannot accurately reflect the wind characteristics at the bridge site. Recently, the structural health monitoring (SHM) technology has been rapidly developed in the civil engineering community, and this provides abundant valuable information for evaluation of structural integrity, durability and reliability. As to bridge engineering, an SHM system usually contains several monitoring categories and one of the major subsystems is the wind load and response monitoring system.

On the other hand, the joint PDFs of wind speed and direction are commonly employed in research on bridge wind engineering. Due to the complexity and inaccuracy of the discrete joint PDFs [8,13], research efforts have been devoted to the construction of continuous joint PDFs of wind speed and direction. For instance, Weber [22] used an isotropic Gaussian model to describe the wind speed and direction by assuming that the variances of longitudinal and lateral components are the same. In consideration of different variances of these two components, Weber [21] perceived the anisotropic Gaussian model. Qu and Shi [16] applied the Farlie-Gumbel-Morgenstern (FGM) approach to construct the bivariate joint distribution to describe wind speed and air density simultaneously. Johnson and Wehrly [12] used angular-linear (AL) distributions to model the joint distribution of bivariate random variables when one variable is directional and one is scalar. Erdem and Shi [5] modeled seven different bivariate joint distributions by use of the AL, anisotropic lognormal and FGM methods, and then made a comparative study. Carta et al. [3] established the AL distributions with specified marginal distributions and used normal-Weibull mixture distributions to build the marginal distribution of wind speed. However, the above-mentioned indirect modeling approaches usually build the joint distribution function by use of the marginal distributions of two variables, the consequences of which might lead to the deviation between the established joint distribution model and the measured data.

In this study, the stochastic characterization of wind field characteristics of an arch bridge is presented by analyzing the long-term wind monitoring data collected by the SHM system installed on the bridge. For the sake of describing the distribution features of the average wind, the genetic algorithm (GA)-based finite mixture modeling approach is proposed to construct the joint PDF of the average wind speed and direction. The Weibull distribution and the von Mises distribution are used to represent the distribution of the wind speed and direction, respectively. The GA-based parameter estimation method is employed to estimate the parameters of in the mixed distribution models. The optimal models are selected by use of the Akaike's information criterion (AIC), Bayesian information criterion (BIC) and R^2 value. The results of the joint PDF of the wind speed and direction formulated by the proposed approach are compared with those obtained by use of the traditional AL distribution-based modeling approach.

2. Long-term monitoring of wind field characteristics

2.1. Description of the instrumented arch bridge

The Jiubao Bridge, with an overall length of 1855 m, is the first river-crossing arch bridge in China composed of a steel-concrete composite structure, which was opened to traffic on 6 July 2012. The bridge is located in Hangzhou, China and was built across the Qiantang River. The superstructure of the main bridge comprises a 3×210 m beam-arch composite structure and an 85 m composite box girder in the approaching bridge. The bridge deck is constructed with six traffic lanes and double-sided pavements, and the planned vehicle travel speed is set as 80 km/h.

The wind environment of the bridge site is complicated and dominated by both the monsoon climate and typhoons. The climate condition around the Jiubao Bridge pertains to the humid subtropical with four distinct seasons. The monsoon circulation at the bridge site has a significant influence on the seasonal changes of local weather patterns. The southeast wind from the eastern sea in the summer and the north wind from northwest Siberia in the winter compose the primary wind loading acting on the Jiubao Bridge. Furthermore, in the summer, the bridge usually suffers from several typhoons. Fig. 1 illustrates the wind rose diagrams in the summer and winter which are compatible with the monsoon climate.

2.2. Monitoring of wind field

An SHM system was instrumented on the Jiubao Bridge to monitor the integrity, durability and reliability of the bridge during the in-service stage. The SHM system is mainly designed to monitor eight categories of structural physical quantities of the bridge, namely, deck geometry, temperature and humidity, wind loading, stress and strain, cable force, structural vibration, traffic loading, and support displacement. The sensory system consists of approximately 350 sensors and the condition of the bridge is continuously measured by these sensors. The sensory system includes anemometers, temperature and humidity sensors, a weigh-in-motion system, accelerations, seismic sensors, and cable force sensors.

In order to collect the wind field data near the bridge site during the construction and operation stages, two mechanical anemometers and one ultrasonic anemometer were installed on the Jiubao Bridge. One mechanical anemometer (ANE_L4) and one ultrasonic anemometer (UAN_L6) were installed on the upstream and downstream side of the bridge at the north of the main bridge, and the other mechanical anemometer (ANE_L35) was installed at the south of the main bridge. In order to minimize the effect of traffic on the accuracy of the measured wind field data, the anemometers were installed at approximately 6 m above the bridge deck. For the wind loading monitoring system, the wind direction angle 0° denotes north and 90° denotes east, rotating in a clockwise direction. The sampling frequency of the ultrasonic anemometer is set at 4 Hz and the sampling frequency of the mechanical anemometer is set at 0.1 Hz. The anemometer is able to detect a wind speed ranging from 0 to 60 m/s with an error within 0.01 m/s, and wind direction ranging from 0 to 360° (no dead angle) with an error within 0.1°.

2.3. Average wind speed and direction

In the study, the wind data collected by the ultrasonic anemometer (UAN_L6) are selected to analyze the wind field characteristics, and the data from the mechanical anemometers are used to verify the results. The recorded wind data include the wind speed time series $u(t)$ and the wind direction time series $\phi(t)$, and