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Statistical analysis of wind characteristics of a railway arch bridge based on long-term monitoring data

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ABSTRACT

Analysis of wind characteristics of in-service railway bridges is crucial for structural serviceability and safety evaluation. As an important part of wind field analysis, the precise joint distribution of wind speed and direction at the bridge site is vital for the estimation of the wind-induced dynamic excitation of long-span railway bridges. In this study, a genetic algorithm (GA)-based finite mixture modeling approach is developed to construct the joint probability density function (JPDF) of the wind speed and direction which can describe the wind characteristics nearby the bridge site. The Weibull mixture distributions are used to represent the marginal distribution of wind speed, while the marginal distribution of wind direction adopts a finite mixture of von Mises distributions. In addition, a GA-based mixture parameter estimation method is proposed to estimate the parameters of the JPDF of wind speed and direction. The formulated JPDF of wind speed and direction by the proposed approach is compared with that calculated by traditional AL distribution-based modeling approach in accordance with the values of Akaike's information criterion (AIC) and R^2 statistic. The obtained results indicate that the GA-based finite mixture modeling approach has a favorable capability in constructing the JPDF of wind speed and direction.

1. INTRODUCTION

In recent years, a significant number of long-span railway bridges have been built in China. As the increase of bridge span, the structural stiffness of the railway bridge is reduced significantly and the sensitivity to wind-induced dynamic excitation is expanded (Wang et al. 2009). Thus, the understanding of the structural behaviors of long-span railway bridges located in wind-prone regions is of great importance to the structural

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design and safety assessment. Because the wind characteristics are varying with the geographical condition, the analysis of site-dependent wind features is significant to implement accurate wind-induced bridge aerodynamic research (Herb et al. 2007), and the appropriate way to obtain the realistic response of a bridge under wind loading is to investigate the field monitoring data nearby the bridge (Li et al. 2002). Amongst the currently available methods, the joint probability distribution method has been a widely used statistical method to analyze the characteristics of measured wind data (Cook 1982). However, the usage of inaccurate probability density function (PDF) models may cause the significant errors of estimated structural damage, and thus it is essential to construct the accurate joint distribution model of wind speed and direction (Alduse et al. 2015).

This paper presents the probabilistic modeling of wind characteristics by using the long-term wind monitoring data obtained by a structural health monitoring (SHM) system instrumented on a railway arch bridge located in China. In order to construct the accurate joint probability density function (JPDF) of wind speed and direction, a genetic algorithm (GA)-based finite mixture modeling approach is developed. In the proposed modeling approach, the Weibull distribution and von Mises distribution are used to represent the distribution of wind speed and direction, respectively. In addition, the parameters of the finite mixed model are estimated by the GA-based mixture parameter estimation method. Furthermore, a comparative study is conducted between the tradition AL approach and the proposed modeling approach. The effectiveness of the proposed approach is evaluated the values of Akaike's information criterion (AIC) and R^2 statistic.

2. METHODOLOGY

2.1 *Genetic algorithm-based finite mixture model*

The traditional indirect modeling approach constructs the joint distribution by marginal distributions of two variables respectively, thus it is unavoidable that the distinction exists between the joint distribution models and measured data. In the study, a bivariate finite mixture model is proposed to directly construct the JPDF of wind speed and direction. The wind speed and direction data are assumed to be statistical independence and the PDF of the bivariate finite mixture model for the wind speed $v \in [0, \infty]$ and the wind direction $\theta \in [0, 2\pi]$ is defined by:

$$f(v,\theta) = \sum_{k=1}^{K} w_k f_v(v) f_\theta(\theta) \tag{1}$$

where $f(v, \theta)$ is the JPDF of wind speed and direction, $f_v(v)$ is the PDF of wind speed and $f_\theta(\theta)$ is the PDF of wind direction, and w_k is the weight of each mixture component and satisfies the following:

$$\sum_{k=1}^{K} w_k = 1 \text{ and } 0 < w_k < 1 \tag{2}$$

In the finite mixed model, the Weibull distribution (Weibull 1951) is chosen to represent the distribution of wind speed and the von Mises distribution (Carta et al. 2008) is adopted to represent the distribution of wind direction, which is formulated by:

$$f(v,\theta|c,k,\mu,\kappa) = \sum_{k=1}^{K} w_k \frac{k_k}{c_k}\left(\frac{v}{c_k}\right)^{k_k-1} \exp\left[-\left(\frac{v}{c_k}\right)^{k_k}\right] \cdot \frac{1}{2\pi I_0(\kappa_k)} \exp[\kappa_k cos(\theta - \mu_k)] \tag{3}$$

where c and k are the shape parameter and scale parameter of Weibull distribution respectively, μ and κ are the location parameter and concentration parameter of von Mises distribution respectively.

2.2 Parameter estimation of finite mixed model

Genetic algorithm (GA), proposed by Holland in 1975 (Holland 1975), is a stochastic algorithm for handling optimization problems which have been widely applied to a variety of problems from fields that include mathematics, civil engineering and astronautics (Paulo et al. 2016). A genetic algorithm is an optimization process which through selection and modification of individual solutions to successive approach to the optimal solution. This optimization process is similar to the theory of evolution. Like the feature of biological evolution, the genetic algorithm also possesses the advantage of enabling it to search global area and prevent it from falling to the local optimum. Therefore, a genetic algorithm is especially suitable for complex and high-dimension optimization problem.

The establishment of the fitness function is the crucial part of the genetic algorithm. Assuming that we have a sample $\boldsymbol{x} = [\boldsymbol{x}_1, \boldsymbol{x}_2, \boldsymbol{x}_3, \ldots, \boldsymbol{x}_n]^{\mathrm{T}}$ of n independent and identically distributed wind data, the joint density function (likelihood function) of all wind data is

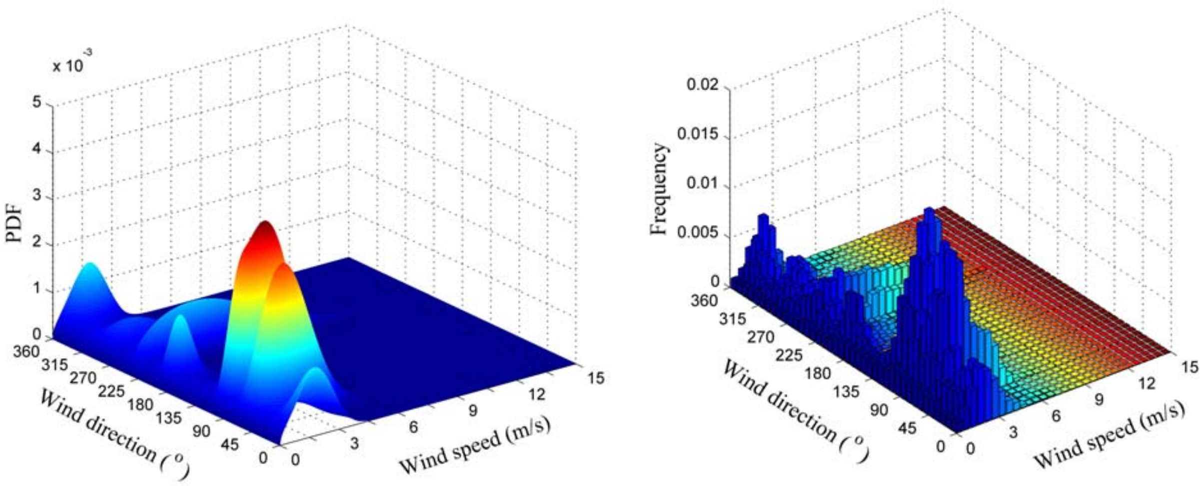
$$f(x_1, x_2, \ldots, x_n|\theta) = f(x_1|\theta) \times f(x_2|\theta) \times \ldots \times f(x_n|\theta) \tag{4}$$

For a certain amount of wind data and the underlying finite mixture model, the method of maximum likelihood can estimate the fit performance of the model parameters by the value of the likelihood function. Namely, the higher the value of the likelihood function is, the better the measured data fit the selected model. The natural logarithm of the likelihood function is often convenient for calculating, therefore the log-likelihood is chosen as the fitness function:

$$\text{FITNESS} = \ln L(\theta; x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} \ln f(x_i|\theta) \tag{5}$$

3. APPLICATION

In this study, the wind data recorded by the structural health monitoring (SHM) system of a railway arch bridge are analyzed to obtain the joint distribution of wind speed and direction. A one-year monitoring data of 2015 are extracted for analysis. After obtaining 10-minute mean wind data, the GA-based finite mixture modeling approach is applied to estimate the parameters. A mixture of eight proposed finite mixture models is taken as the JPDF of wind speed and direction, as shown in Fig. 1(a). In addition, Fig. 1(b) presents the histogram of wind speed and direction. In order to authenticate the suitable of GA-based finite mixture modeling approach, a comparison case is made between the tradition AL-based approach and the proposed approach by the values of AIC and R^2 statistic. As shown in Table. 1, the AIC value of proposed approach is smaller than AL-based approach and the R^2 statistic of proposed approach is also larger. It is obvious that the proposed GA-based finite mixture modeling approach has a better performance.



(a) Joint PDF of wind speed and direction (b) Histogram of wind speed and direction

Fig.1 Joint distribution of wind speed and direction by proposed approach

Table. 1 Comparison between AL approach and proposed approach

	AIC	R^2
GA-based modeling approach	282677.209	0.939
AL-based modeling approach	298681.247	0.794

4. CONCLUSIONS

In this study, the GA-based finite mixture modelling approach is applied to construct the joint distribution of wind speed and direction. The GA is used to estimate the parameters of the finite mixture distribution. Through examining the values of AIC and *R* squared, the optimal probability distribution model is determined. The long-term wind monitoring data are collected by the SHM system instrumented on a railway arch bridge located in China, the proposed procedure for modelling the joint probability distribution model of wind speed and direction is exemplified. The wind speed and direction data are characterized by the mixture of Weibull distributions and von Mises distributions, respectively. The comparison between the proposed GA-based modeling approach and AL-based modeling approach using one-year wind data shows that the proposed approach exhibits better performance.

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