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Uncertainty propagation in buffeting fragility analysis of long-span bridges using surrogate models

Xiaonong Hu [1], Genshen Fang [1,2], Yaojun Ge [1,3]

[1] State Key Lab of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China,
2210016@tongji.edu.cn
[2] 2222tjfgs@tongji.edu.cn
[3] yaojunge@tongji.edu.cn

SUMMARY:
The randomness of aerodynamic and structural parameters results in great dispersion of buffeting responses of the bridge. The adoption of direct Monte Carlo (MC) method to account for these uncertainties usually cost enormous computational resource. This research presents an efficient framework based on surrogate models for uncertainty propagation from flutter derivatives (FDs) and damping ratio to buffeting responses and assessment of structural fragility for a long-span bridge. After performing Sobol sensitivity analysis to select several key parameters that directly determine the buffeting response of the bridge, the feasibility to substitute the original buffeting calculation procedure with surrogate models is examined. Compared with direct MC method, Kriging model is found to be a favourable surrogate model. Based on constructed Kriging model, MC simulations are performed to obtain uncertain buffeting responses. Associated with four performance levels, fragility curves are obtained to describe the conditional exceedance probability at a given mean wind speed.

Keywords: Uncertainty propagation, fragility analysis, surrogate models

1. INTRODUCTION

Buffeting of bridges is a limited amplitude forced vibration which can occur at boundary layer winds. Although buffeting won’t cause catastrophic damage, it may lead to large structural deformation, component fatigue and problems of user comfort. Evaluation of structural buffeting responses attracts wide concerns, where the frequency-domain method is basically used. In frequency domain analysis, two types of key parameters are involved, flutter derivatives (FDs) and damping ratio. There are inevitably some uncertainties caused by factors like equipment defects, leading to uncertain dynamic responses. To explore uncertainty propagation, probability-based approaches can be applied, for example, calculating the fragility function or failure probability by widely used Monte Carlo (MC) method (Seo and Caracoglia, 2012). Lots of simulations would be generally required, costing considerable computing time. To enhance efficiency, surrogate models have been developed and widely utilized recently. The aim of surrogate models is to use as few high-precision sample points as possible to build accurate surrogate models, that is, to replace complex and time-consuming calculations with simple functions. Among different surrogate models, the Kriging method has high accuracy and performs well for both global and local estimation (Li et al., 2022). Apart from that, the method of polynomial chaos expansions (PCE) is also an effective method for uncertainty analysis. To substitute the original calculation procedure, PCE method generally employs orthogonal polynomials as basic functions to construct response surface (Rogier, 2022). The objective of this study is to develop an efficient framework by surrogate models (PCE and Kriging) for uncertainty propagation from FDs and damping ratio to buffeting responses and fragility assessment of long-span bridges.

2. PCE AND KRIGING MODELS

The PCE model can be expressed as the product of the PCE coefficients a_i and the orthogonal polynomials ϕ_i of the random variable η. Taking the response of interest Y as an example, its PCE model can be briefly formulated as (Rogier, 2022)

$$Y = \sum_{i=0}^{\infty} a_i \phi_i(\eta) \tag{1}$$

Similarly, Kriging model assumes that the response value of the system is a random function $y(x)$, which consists of a regression model and a random error $z(x)$:

$$y(x) = \sum_{i=1}^{k} \beta_i f_i(x) + z(x) = \boldsymbol{f}^T(x)\boldsymbol{\beta} + z(x) \tag{2}$$

where $\boldsymbol{f}^T(x) = [f_1(x), \cdots, f_k(x)]$ is the regression polynomial vector, $\boldsymbol{\beta} = [\beta_1, \cdots, \beta_k]^T$ is the vector of unknown coefficients.

3. DESCRIPTION OF THE BRIDGE STRUCTURE AND RANDOM PARAMETERS

The bridge involved in this study is located in Pearl River estuary, Guangdong Province of China. It is a suspension bridge with main span *l*=1666 m and deck width *B*=49.7 m, as shown in Fig. 1.

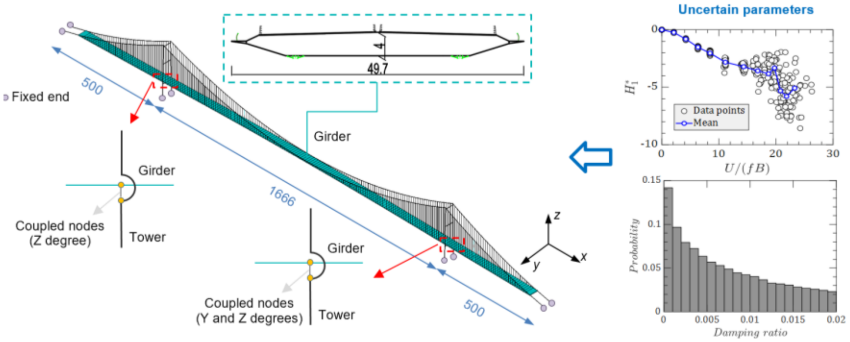

Figure 1. Suspension bridge model and related uncertain parameters.

Uncertainties are mainly attributed to the randomness of FDs measured from physical experiments and structural damping ratios (see Fig. 1). The FDs are identified by 30 repeated wind tunnel tests so that 30 sets of FDs can be analysed. As a result, the mean values and standard deviations of FDs are adopted as parameters of normal distributions which are taken as probability models of FDs. As for damping ratio ζ, the Weibull distribution with a scale parameter of 1.83 and a shape parameter of 0.80 is used referred to Kwon (2010). In combination with the real engineering, the sampling of damping ratio is truncated at 0.02. After applying Sobol sensitivity analysis method, it is found that 3 FDs (H_1^*, A_2^* and A_3^*) and damping ratio have major impact on the buffeting responses. Therefore, uncertainties of these parameters are considered.

4. FRAGILITY ANALYSIS USING SURROGATE MODELS

Before construction of surrogate models, it is essential to select some effective sample points. Latin Hypercube Sampling (LHS) was adopted in this study to draw initial points. Since the PCE model should be constructed in the random space, sample points for PCE were generated by LHS from corresponding random spaces, i.e., the normal distribution for FDs and the uniform distribution for damping ratio. As for the Kriging model, LHS was used to extract initial sample points with the infill sampling criterion of RMSE (root mean square error).

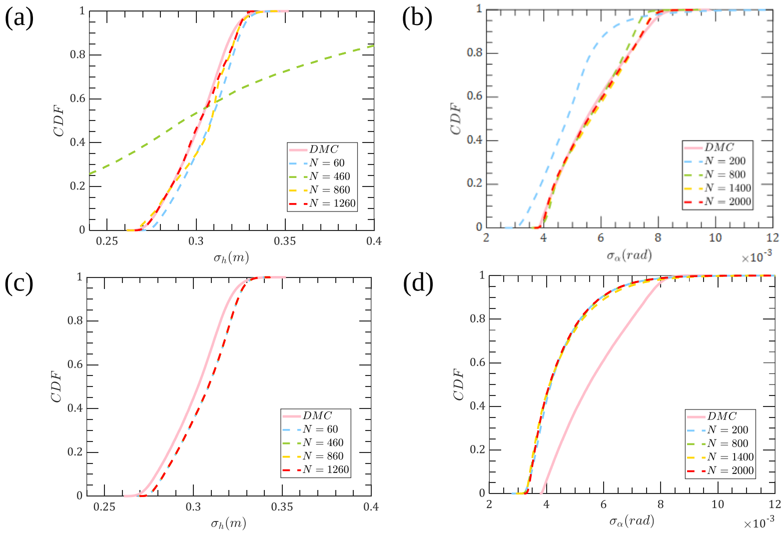

Figure 2. CDF curves of responses from Kriging-MC and PCE-MC models ((a) Kriging, vertical (b) Kriging, torsional (c) PCE, vertical (d) PCE, torsional).

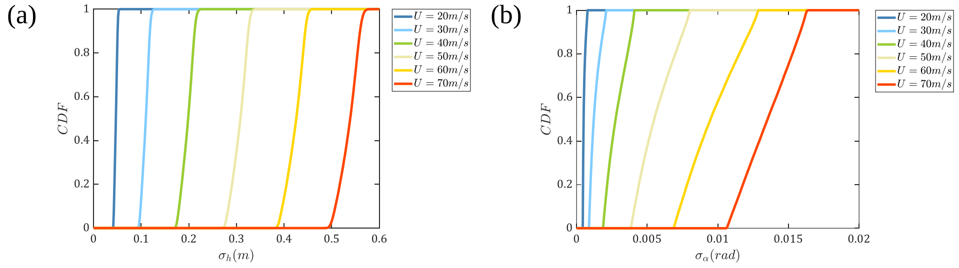

Figure 3. CDF of responses from based on Kriging-MC model at different wind speeds ((a) Vertical (b) Torsional)

To verify reliability of PCE and Kriging models, direct MC (DMC) simulations were performed 50000 times based on the dynamic response calculation procedure, requiring about 17 hours. As shown in Fig. 2, though the results of the Kriging-MC are not presented well at first, the calculation gets improved with the increase of sample points. The vertical CDF (cumulative distribution function) with 1260 points and torsional CDF with 2000 points coincide well with the curves of DMC. By contrast, increasement of samples has little effect on the PCE-MC model. As a result, it’s reasonable to use 1260 and 2000 points to construct the Kriging model for vertical and torsional responses, respectively. By using the constructed Kriging model to calculate buffeting responses, 50000 MC simulations were conducted, which only cost less than one minute. Fig. 3 depicts CDF of dynamic responses corresponding to different wind speeds, and both vertical and torsional responses generally grow with the wind speed. Due to randomness of FDs and damping ratio, dynamic responses are random and uncertain.

In this study, indices of peak acceleration and displacement are considered, including four levels of thresholds as shown in Table 1. And the fragility curves (Fig. 4) show that for all performance levels, probabilities of exceedance increase with the increase of wind speed. Responses of displacement are always lower than the given thresholds with wind speeds lower than 50 m/s. But when it’s higher than 50 m/s, the responses of displacement, especially vertical displacement, begin to surpass thresholds. By contrast, it’s easier for responses of acceleration to achieve and exceed thresholds, indicating that performance related to user comfort might not be so satisfied.

Table 1. Thresholds for different limit states

Limit state	T_1	T_2	T_3	T_4
Vertical	0.3 m/s^2	0.4 m/s^2	1.04m	1.39m
Torsional	0.012 rad/s^2	0.016 rad/s^2	0.042 rad	0.056 rad

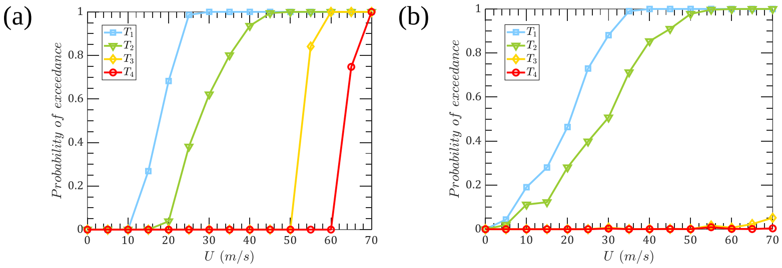

Figure 4. Fragility curves with respect to thresholds ((a) Vertical (b) Torsional)

5. CONCLUSIONS

Considering uncertainties of dominant factors, 3 FDs (H_1^*, A_2^* and A_3^*) and damping ratio, the Kriging model can approximate well with the results of the original procedure globally, which contributes a lot to saving time for MC simulations. Furthermore, for long-span bridges, though structural safety is important, but it tends to be easier to exceed the threshold of user comfort.

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