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Failure modes and probabilistic evaluation of vortex-induced vibration for bridges

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Abstract. Vortex-induced vibration (VIV) of bridges involves many uncertain factors such as wind speed, structural parameters, aerodynamic parameters, etc. So considering the uncertainties of VIV is very meaningful. In this study, failure modes and a calculation method based on reliability theory were proposed to evaluate VIV instability of bridges. Firstly, failure modes for maximum amplitude of VIV in which the influence factor of interval of lock-in wind speed was considered, wind speed, combination of amplitude and wind speed were presented. Secondly, Maximum Entropy (MaxEnt) principle was applied to determine the probability density function (PDF) of performance function of the failure mode for maximum amplitude of VIV. In numerical procedure, the statistical characteristics of all parameters were derived from results of wind-tunnel tests and their empirical distribution functions. Then the failure probabilities of VIV amplitude were calculated for a long-span bridge using second-order fourth-moment (SOFM) method based on MaxEnt principle and Monte Carlo (MC) simulation technique. Finally, on account of the results using SOFM, the failure probabilities for combination of amplitude and wind speed were obtained. The investigations illustrate that the results of the probabilistic approach presented validate the appropriateness through comparison with that of MC method and failure mode based on combination of amplitude and wind speed is more reasonable than that based on wind speed or amplitude alone.

Keywords: bridges; VIV; failue mode; probabilistic evaluation; SOFM; MC

1. INTRODUCTION

Comprehensive research activities in the recent past years have been undertaken in the area of reliability research on wind-induced vibration (RRWV) of bridges based on aeroelastic dynamic response which is related to flutter instability, vortex-induced vibration (VIV) instability and buffeting instability etc. According to most wind-resistant design codes for bridges, safety factor method is still adopted. However, the research on wind-resistant design by using probabilistic limit state design method is still in initial stage and mainly starts with computation method for structural point reliability due to the

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complexity of structure itself and difficulties of mathematical and mechanical analysis.

In the field of RRWV for bridges, the previous work is conducted in the context of a probabilistic investigation using first-order second-moment method, second-order second-moment method, peak over threshold method or stochastic finite element method (FEM) to assess flutter failure probability or buffeting first excursion probability. The investigation of VIV as a typical phenomenon of wind-induced vibration, especially for the bridges, occurring in lock-in low wind speed intervals with limited amplitude when the vortex shedding frequency is close to the natural frequency of the bridge based on probability methods is very rare. Although VIV is a limited amplitude vibration and dose not cause collapse of bridges, it can result in large displacements and discomfort to the drivers. Moreover, it commonly occurs in the low wind speed region, so the occurrence probability of vortex-induced vibration is high, maybe resulting in long-term fatigue damage. It is therefore useful to assess the vortex-induced probability by performing a probabilistic analysis. A stochastic model of vortex-induced force was proposed which afterwards became a calculation method of ESDU for VIV by Barry and Arthur (1972). The effect of VIV caused by high order mode of cable-stayed bridge on wind-resistant reliability was considered in reliability analysis on wind-resistant structures by Prenninger (1990) and it demonstrated that VIV has great influence. The probability for VIV of an arch bridge has been assessed and its essence was occurrence probability of lock-in wind speed (Ge *et al.* 2004). The dispersing of time and space was carried out for vortex-induced force by use of strip hypothesis in conjunction with the second Scanlan's vortex shedding half-empirical and half-analytical model and an Alternating Time Frequency (AFT) domain method was developed to solve the calculation of vortex-induced responses (Li and Liao 2003).

These reliability analysis methods mentioned above have limitations, e.g., due to the accuracy of uncertainty computation for random variables, it is inadequate because of the imperfection of data-information and selected distribution type; the expression of joint PDF for wind-induced vibration failure mode is too complex to directly integrate transformed into elementary function. Existing literature studies have suggested that the flutter probability can be successfully assessed either by the first-order reliability method(FORM) (Dragomirescu *et al.* 2003) or an extension of the "response surface method" (Cheng *et al.* 2005). In both cases some of the parameters used to describe the dynamic response, are treated as random quantities with an appropriate probability distribution. But acturally these probability distributions are mostly the empirical distribution function and reports about precision range are not demonstrated so that in engineering it is inconvenient to judge result precision and special applications. Parameter set for approximating enough precision of first-order and second-order reliability was studied and a general procedure has been proposed for FORM/SORM by Zhao and Ono (1999). Der Kiureghian and Liu (1986) have set forth a comprehensive framework for the analysis of structural reliability under incomplete probability information and a method was developed to incorporate in the reliability analysis incomplete probability information on random variables, including moments, bounds, marginal distributions, and partial joint distributions. The method is consistent with the philosophy of Ditlevsen's generalized reliability index and complements existing second-moment and full-distribution structural reliability theories (Der Kiureghian 1989). Furthermore, fourth moment method was applied in structural reliability theory (Zhao *et*