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Application of inverse reliability method to estimation of flutter safety factors of suspension bridges

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Abstract. An efficient and accurate algorithm is proposed to estimate flutter safety factor of suspension bridges satisfying prescribed reliability levels. Uncertainties which arise from the basic wind speed at the bridge deck location, critical flutter velocity, the wind conversion factor from a scaled model to the prototype structure and the gust speed factor are incorporated. The proposed algorithm integrates the concepts of the inverse reliability method and the calculation method of the critical flutter velocity of suspension bridges. The unique feature of the proposed method is that it offers a tool for flutter safety assessment of suspension bridges, when the reliability level is specified as a target to be satisfied by the designer. Accuracy and efficiency of this method with reference to three example suspension bridges is studied and numerical results validate its superiority over conventional deterministic method. Finally, the effects of various parameters on the flutter safety factor of suspension bridges are also investigated.

Keywords: inverse reliability method; flutter safety factor; suspension bridges; target reliability index; uncertainties

1. Introduction

Flutter instability is one of the problems of major concern in the design of suspension bridges as it can lead to the collapse of the structure (Han *et al.* 2015, Wang *et al.* 2016). Therefore a reasonable safety margin against flutter has to be carefully assured. In the wind resistant design of suspension bridges, a safety factor (γ) is introduced to ensure an acceptable safety margin for suspension bridges against flutter. Traditionally, the flutter safety factor is estimated using a deterministic model. The safety assessments against flutter is accepted or rejected depending on whether the estimated safety factor is within the acceptable value or not. Due to the estimation focus of safety factor commonly used in wind resistant design of suspension bridges, even when conservative safety factors are used, the what safety degree is still unknown. In practice, both the acceptable and estimated safety factors are adjusted entirely based on empiricism. Uncertainties which arise from the extreme wind speed at the bridge location, structural damping and flutter derivative cannot be incorporated within the estimation of flutter safety factors.

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Current bridge design standards have been developed to ensure structural safety by defining a target reliability index (Reid 2002). In other words, the structural reliability level is specified as a target to be satisfied by the designer. Thus, calibration of flutter safety factors is needed to guarantee the specified reliability of suspension bridges. The inverse reliability method can be pursued for the calibration of flutter safety factors satisfying prescribed reliability. The basic idea of the method is to determine the unknown parameter considered in the design such that a prescribed target reliability index is reached. In recent years, many efforts have been focused on the development of the method and/or application of the method in different design problems. Winterstein *et al*. (1993) utilized this method for the estimation of design loads associated with specified target reliability levels for offshore structures. An extension of the method was developed by Der Kiureghian *et al*. (1994) for general limit state functions. Li and Foschi (1998) introduced an inverse reliability method for determining design parameters, and applied it to problems of earthquake and offshore engineering. Fitzwater *et al*. (2003) applied inverse reliability methods for extreme loads on pitch- and stall-regulated wind turbines. Saranyaseontorn and Manuel (2004) extended the inverse reliability method to estimate nominal loads for the design of wind turbines against ultimate limit states. Lee *et al*. (2008) proposed an inverse reliability analysis method for reliability-based design optimization (RBDO) of nonlinear and multi-dimensional systems by developing the most probable point (MPP)-based dimension reduction method (DRM). More recently, Xiang and Liu (2011) developed an inverse reliability method for probabilistic fatigue life prediction.

Although the inverse reliability method founds some applications for different design problems, its application to calibration of flutter safety factors of suspension bridges has not been reported. Therefore, the purpose of the current study is to apply the inverse reliability method to estimate flutter safety factors of suspension bridges satisfying prescribed reliability. On this purpose, this paper first presents the mathematical formulation of the calibration problem of flutter safety factors of suspension bridges. Secondly, an efficient algorithm is proposed to solve the calibration problem of flutter safety factors of suspension bridges. Finally, the proposed method is applied to calibration of flutter safety factors for three suspension bridges.

2. Calibration problem of flutter safety factors

For a target reliability index β_t, the calibration problem of flutter safety factors can be described by

find the flutter safety factor γ, which minimizes $\beta_t = \|\mu\|$ (1)

subject to $G(\mu,\gamma) = 0$

where $G(\mu,\gamma)$ represents the transformation of the limit state function $g(X,\gamma)$ from the original space to the space of standard normal variable. μ is the vector of standard normal variables, and X represents the vector of basic random variables. Here the basic wind speed at the bridge deck location, V_b, critical flutter velocity, V_{cr}, the wind conversion factor from a scaled model to the prototype structure, C_w and the gust speed factor, G_s are taken as random variables(Ge *et al*. 2000, Ge *et al*. 2008). The limit state function for flutter reliability of suspension bridges

$g(X,\gamma)$ is of the form

$$g = C_w \cdot V_{cr} - \gamma \cdot G_s \cdot V_b \tag{2}$$

3. Proposed estimation method of flutter safety factors

The proposed estimation method of flutter safety factors is a hybrid method, consisting of the calculation method of the critical flutter velocity, V_{cr} and inverse reliability method. The method is based on two key concepts: (1) the determination of critical flutter velocity by the simplified approach (or finite element method or wind-tunnel tests); and (2) estimation of the flutter safety factors using the inverse reliability method. The details of these concepts are described in the following sections.

3.1 Determination of critical flutter velocity

The critical flutter wind speed, V_{cr} can be determined directly by wind-tunnel tests observing the behavior of aeroelastic models which respect as many similitude parameters as possible. Alternatively, the finite element method and empirical formula can be employed to analyze the flutter response of the bridge. A brief description of the two methods is presented next.

The equations of motion with respect to the static equilibrium position of a bridge caused by the self-excited aerodynamic forces can be expressed as (Zhang *et al*. 2003)

$$[M]\{\ddot{q}(x,t)\} + [D]\{\dot{q}(x,t)\} + [K]\{q(x,t)\} = \{F_{se}\} \tag{3}$$

$$\{F_{se}\} = \frac{1}{2}\rho U^2 ([A_s]\{q(x,t)\} + \frac{1}{U}[A_d]\{\dot{q}(x,t)\})$$

where [M] is the mass matrix ; $[D]$ is the structural damping matrix; [K] is the stiffness matrix; $\{F_{se}\}$ represents the vector of the self-excited aerodynamic forces acting on the bridge; $\ddot{q}(x,t), \dot{q}(x,t), q(x,t)$ are the vectors of acceleration, velocity and displacement, respectively; $[A_s]$ and $[A_d]$ are the aerodynamic stiffness matrix and aerodynamic damping matrix, respectively; ρ is the air density; and U is the mean wind velocity.

By introducing the displacement transformation $\{q(x,t)\} = [\phi]\{\xi(t)\}$, where $[\phi]$ is the mode shape matrix; $\{\xi(t)\}$ is the generalized coordinate vector, and by assuming that the generalized coordinates have a damped harmonic form, Eq.(3) can be expressed as (Lau *et al*. 2000)

$$\left[[M]^g (\frac{U}{B})^2 P^2 + [D]^g (\frac{U}{B})P + [K]^g - \frac{1}{2}\rho U^2 ([A_s]^g + \frac{1}{B}[A_d]^g P)\right]\{R\}\exp(\frac{U}{B}Pt) = \{0\} \tag{4}$$

$$[M]^g = [\phi]^T [M][\phi], [D]^g = [\phi]^T [D][\phi], [K]^g = [\phi]^T [K][\phi] \tag{5}$$

$$[A_s]^g = [\phi]^T [A_s][\phi], [A_d]^g = [\phi]^T [A_d][\phi] \tag{6}$$

where $[M]^g, [D]^g, [K]^g$ are the generalized mass, damping and stiffness matrices, respectively; $[A_s]^g, [A_d]^g$ are the generalized aerodynamic stiffness matrix and aerodynamic damping matrix, respectively; $P = k(\delta + i)$; k is the reduced frequency; δ is the logarithmic decrement; and {R} is the response amplitude.

To obtain a nontrivial solution for Eq. (4), the determinant of the expression in the square bracket must be zero (Lau *et al*. 2000). The PK-F method (Namini and Albrecht 1992), modified from the P-K method (Hassig 1971) used in the aircraft industry for solving the flutter problem of airfoils, is employed for the solution of the flutter problem of bridges. For the given range of wind velocity, the critical flutter wind velocity can be determined by iteration of the flutter determinant. For more details concerning the finite element method for flutter analysis of bridges, the reader is referred to (Cai 1993).

The empirical formula has the form (CCCC Highway Consultants Co., Ltd 2004)

$$V_{cr} = \eta_s [1 + (\varepsilon - 0.5)\sqrt{0.72\mu(\frac{r}{b})}] \cdot \omega_b \cdot b \quad (7)$$

$$\mu = \frac{m}{\pi \rho b^2} \quad (8)$$

where V_{cr} =critical flutter velocity, which is a random variable in Eq. (2); η_s =shape coefficient of the bridge deck that is given in Ref. (CCCC Highway Consultants Co., Ltd 2004); ε =frequency ratio between fundamental torsional and bending modes; r = radius of gyration of the bridge deck; m =mass per unit length of the stiffened girder and main cables; ρ =air density; b =the half-deck width; and ω_b =circular frequency of the first bending mode.

3.2 Estimation of the flutter safety factors

As stated in Ref. (Li and Foschi 1998), the above-mentioned calibration problem of flutter safety factors can be solved by “trial and error”, using a forward reliability method like FORM and varying the safety factor, γ until the reliability achieved matches with the required target. The trial and error procedure is inefficient and involves difficulties resulting from repetitive forward reliability analysis. Thus, it is desired to develop an efficient and more direct approach to determine the design parameters for specified target reliabilities. A general inverse reliability methodology is proposed in the paper, which allows the direct determination of the safety factor when the corresponding target reliabilities are given. The proposed algorithm is similar to the inverse reliability method developed by Der Kiureghian *et al*. (1994). The algorithm involves an iterative algorithm given by the following recursive formulae

$$\mu^{k+1} = \mu^k + \lambda^k d\mu^k \quad (9)$$

$$\gamma^{k+1} = \gamma^k + \lambda^k d\gamma^k \quad (10)$$

$$d\mu^k = -\beta_t \frac{\nabla_\mu G(\mu^k, \gamma^k)}{\left\| \nabla_\mu G(\mu^k, \gamma^k) \right\|} - \mu^k \tag{11}$$

$$d\gamma^k = \frac{\left[\nabla_\mu G(\mu^k, \gamma^k), \mu^k \right] - G(\mu^k, \gamma^k) + \beta_t \left\| \nabla_\mu G(\mu^k, \gamma^k) \right\|}{\nabla_\gamma G(\mu^k, \gamma^k)} \tag{12}$$

where μ^k is the vector of standard normal variables at the k th iteration, γ^k represents the deterministic design parameter at the k th iteration, ∇_μ is a vector of gradient operators with respect to μ, ∇_γ is a vector of gradient operators with respect to γ, $[,]$ is the inner product of two vectors, λ^k is the step size at k th iteration, which is determined through a line search algorithm proposed by Der Kiureghian *et al*. (1994). The algorithm proceeds iteratively until convergence is achieved, i.e., when

$$\frac{(\left\| \mu^{k+1} - \mu^k \right\|^2 + \left| \gamma^{k+1} - \gamma^k \right|^2)^{1/2}}{(\left\| \mu^{k+1} \right\|^2 + \left| \gamma^{k+1} \right|^2)^{1/2}} \le e \tag{13}$$

where e is a small control parameter assigned by the user. From the past authors' experience, a value of $e = 10^{-4}$ to 10^{-3} usually provides satisfactory γ estimates.

3.3 Procedure for the proposed method

The procedure of the proposed method is:

1. Assume the initial values of the random variables and an unknown deterministic design parameter. The initial values of the random variables can be their mean values.
2. Initialize the iterative counter $k = 1$.
3. Calculate $d\mu^k$ and $d\gamma^k$ from Eqs. (11) and (12).
4. Substitute $d\mu^k$ and $d\gamma^k$ into Eqs. (9) and (10), the values of μ^{k+1} and γ^{k+1} are determined.
5. Check the convergence criterion using Eq. (13), If unsatisfied, set $k = k + 1$ and go to Step 3; otherwise, STOP (end of calculation).

For comparison purposes, three methods are considered in the present study. Method I is the proposed method based on wind-tunnel tests in order to determine the critical flutter velocity. Method II is the proposed method based on finite element method described previously. Method III is the proposed method based on empirical formula given by Eq. (7).

4. Application to suspension bridges

4.1 Description of suspension bridges considered

Three suspension bridges built in China were chosen for this study. They are Hu Men Bridge with a 888 m central span length, Jiang Yin Yangtze Bridge with a 1385 m central span length and the Fourth Nanjing Yangtze Bridge with a 1418m central span length, respectively. The basic data of these bridges are given as follows:

Hu Men Bridge is the first long-span suspension bridge in China. The bridge span arrangements are (302+888+348.5) m. The elevation view of the bridge is shown in Fig. 1. The deck cross-section is an aerodynamically shaped closed box steel girder with 35.6 m wide and 3.012 m high. The cross section of the bridge deck is shown in Fig. 2. The distance between two cables is 33m, and the hanger spacing is 12.0 m. For more details, the reader can refer (Xiao and Cheng 2004).

Jiang Yin Yangtze Bridge is one of the longest suspension bridges in China. The bridge span arrangements are (336+1385+309) m. The elevation view of the bridge is shown in Fig. 3. The deck cross-section is an aerodynamically shaped closed box steel girder with 36.9 m wide and 3.0 m high. The cross section of the bridge deck is shown in Fig. 4. The distance between two cables is 32.5 m, and the hanger spacing is 16.0 m. For more details, the reader can refer (Cheng *et al*. 2002, Gu *et al*. 2000).

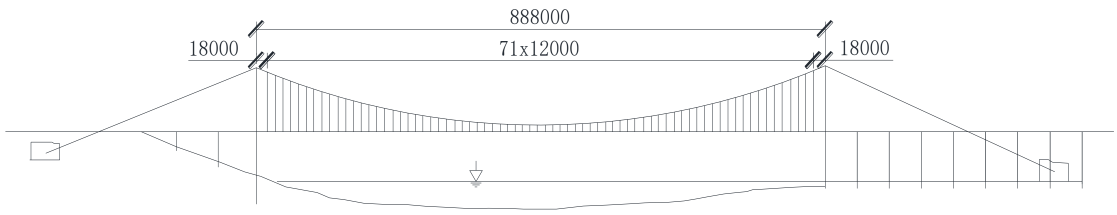


Fig. 1 Elevation of Hu Men Bridge (unit: mm)

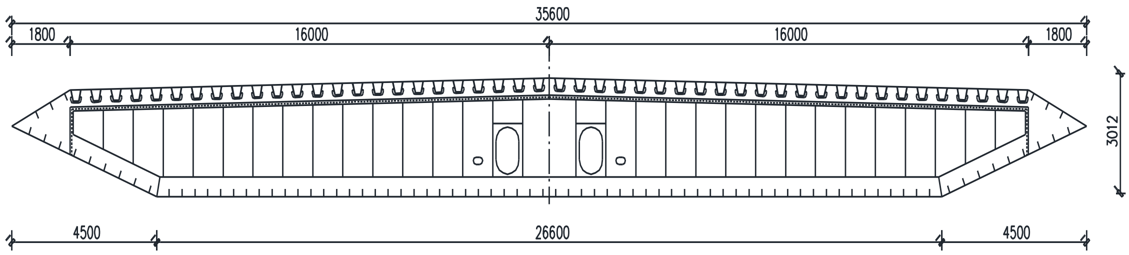


Fig. 2 Deck cross section of Hu Men Bridge (unit: mm)

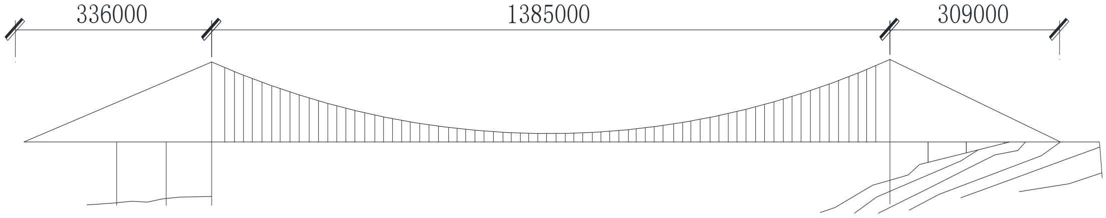


Fig. 3 Elevation of Jiang Yin Yangtze Bridge (unit: mm)

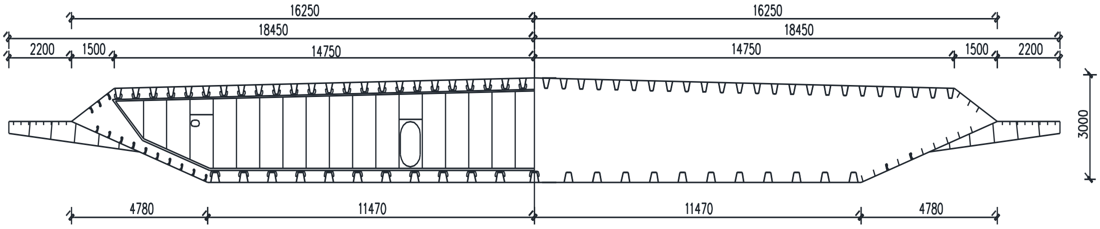


Fig. 4 Deck cross section of Jiang Yin Yangtze Bridge (unit: mm)

The Fourth Nanjing Yangtze Bridge is a three-span steel box girder suspension bridge. The bridge span arrangements are (576.2+1418+481.8) m. The elevation view of the bridge is shown in Fig. 5. The deck cross-section is an aerodynamically shaped closed box steel girder with 38.8 m wide and 3.5 m high. The cross section of the bridge deck is shown in Fig. 6. The distance between two cables is 34 m, and the hanger spacing is 15.6 m. For more details, the reader can refer (Southwest Jiaotong University 2007).

The basic parameters used in Eq. (7) for suspension bridges considered in this paper are listed in Table 1.

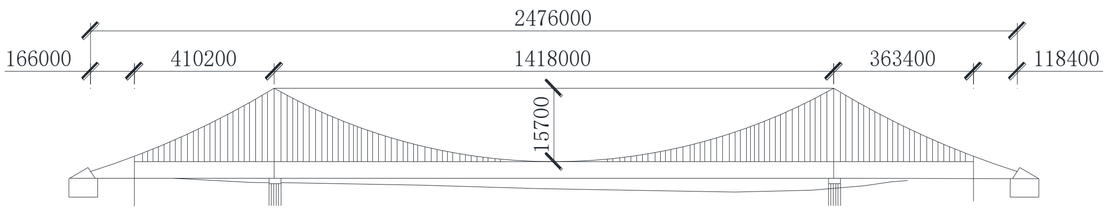


Fig. 5 Elevation of Fourth Nanjing Yangtze Bridge (unit: mm)

Table 1 The basic parameters used in Eq. (7) for suspension bridges considered in this paper

Bridge name	m (kg/m)	I_m (kg. m^2/m)	ω_t (Hz)	ω_b (Hz)	ρ (kg/m^3)	b (m)	Sources
Hu Men bridge	18773	2052000	0.426	0.122	1.225	17.8	(Chen 2013)
Jiang Yin Yangtze Bridge	26680	3687800	0.2677	0.089	1.225	18.45	(Ge 2011)
Fourth Nanjing Yangtze Bridge	22360	2166010	0.2627	0.1142	1.225	19.4	(Ge *et al*. 2000)

(Notes: m is the mass per unit length of bridge deck; I_m is the mass moment of inertia per unit length of bridge deck; ω_i is the torsional circular frequency; ω_b is the bending circular frequency; ρ is the density of air; b is the half-width of the bridge deck)

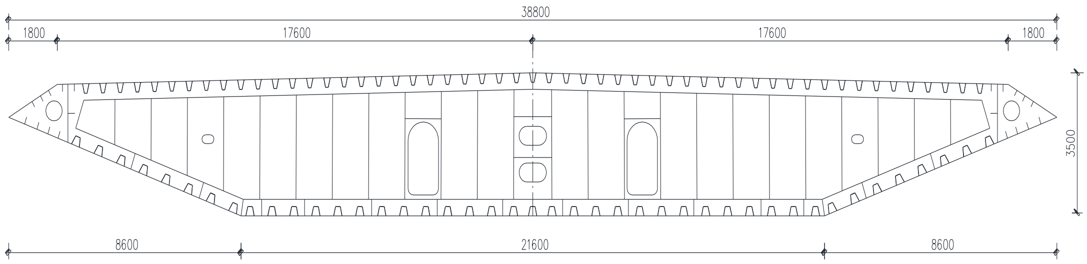


Fig. 6 Deck cross section of Fourth Nanjing Yangtze Bridge (unit: mm)

4.2 Uncertainties of the suspension bridges

As previously mentioned, the basic wind speed at the bridge deck location, V_b, critical flutter velocity, V_{cr}, the wind conversion factor from a scaled model to the prototype structure, C_w and the gust speed factor, G_s are taken as random variables due to their natures and/or insufficient measured data, experimental error and wind characteristics. Tables 2-4 show the statistics of these random variables for each suspension bridge considered in this paper. Since the determination of the interrelation of the random parameters is a difficult task, using the independence assumption can greatly simplify the solution of flutter safety factors of suspension bridges. Therefore, all random parameters in the paper are treated as stochastically independent from each other.

4.3 Estimation of flutter safety factors using different proposed methods

To estimate flutter safety factors using the three proposed algorithms mentioned previously, the target reliability level needs to be specified for the limit state considered in this study. Recent studies by (Ge and Xiang 2008) reveal that the reliability index of suspension bridges against flutter lies in an approximate range of 3.0-4.5.

Table 2 Random variables and their statistical properties of Hu Men Bridge

Random variable	Mean value	COV	Distribution type	Sources
C_w	1	0.05	Normal	(Ge *et al*. 2000)
V_{cr}	88 (empirical formula)	0.075	Lognormal	(Ge and Xiang 2008, Ge *et al*. 2000)
	75.2 (finite element)			(Chen 2013, Ge *et al*. 2000)
	79 (wind tunnel test)			(CCCC Highway Consultants Co., Ltd 2004, Ge *et al*. 2000)
G_s	1.206	0.07	Normal	(Ge and Xiang 2008, Ge *et al*. 2000)
V_b	27.92	0.2	Extreme type I	(Ge and Xiang 2008)

Hence, a target reliability index of 3.2 is considered for this study unless otherwise stated. In the following analyses, unless stated, otherwise, the initial values for the random variables shown in Tables 2-4 are selected to be mean value and γ = 1.5. The results are given in Table 5. Fig. 7 shows that the convergence is achieved for all suspension bridges considered in this paper using the proposed algorithms. The results are confirmed by forward reliability analysis.

Table 3 Random variables and their statistical properties of Jiang Yin Yangtze Bridge

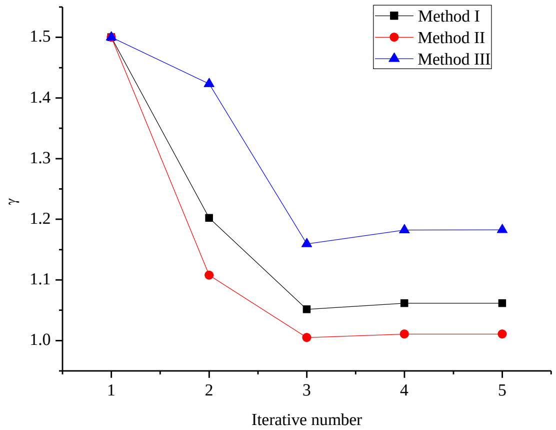
Random variable	Mean value	COV	Distribution type	Sources
C_w	1	0.05	Normal	(Ge *et al*. 2000)
V_{cr}	74 (empirical formula)	0.075	Lognormal	(Ge and Xiang 2008, Ge *et al*. 2000)
	66.8 (finite element)			(Gu *et al*. 2000, Ge *et al*. 2000)
	67 (wind tunnel test)			(Ge 2011, Ge *et al*. 2000)
G_s	1.194	0.07	Normal	(Ge and Xiang 2008, Ge *et al*. 2000)
V_b	21.63	0.2	Extreme type I	(Ge and Xiang 2008)

Table 4 Random variables and their statistical properties of Fourth Nanjing Yangtze Bridge

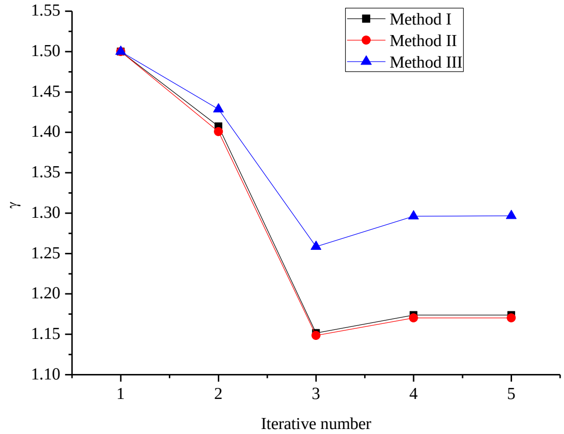
Random variable	Mean value	COV	Distribution type	Sources
C_w	1	0.05	Normal	(Ge *et al*. 2000)
V_{cr}	80.08 (empirical formula)	0.075	Lognormal	(Ge and Xiang 2008, Ge *et al*. 2000)
	72.24 (finite element)			(Southwest Jiaotong University 2007, Ge *et al*. 2000)
	74.1 (wind tunnel test)			(Southwest Jiaotong University 2007, Ge *et al*. 2000)
G_s	1.19	0.07	Normal	(Ge and Xiang 2008, Ge *et al*. 2000)
V_b	25.9	0.2	Extreme type I	(Ge and Xiang 2008)

Table 5 Flutter safety factors of the suspension bridges considered in this paper using the proposed algorithms

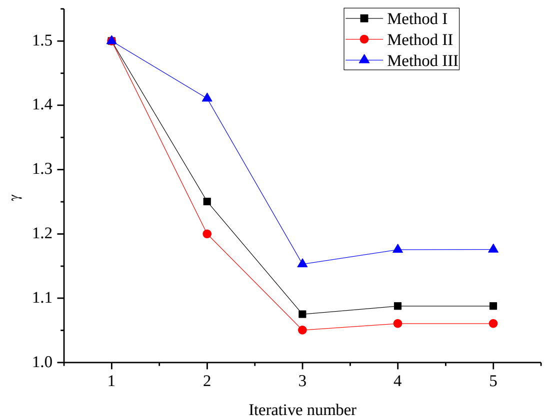
Bridge name	Flutter safety factors		
	Method I	Method II	Method III
Hu Men Bridge	1.0617	1.0106	1.1826
Jiang Yin Yangtze Bridge	1.1739	1.1704	1.2966
Fourth Nanjing Yangtze Bridge	1.0879	1.0606	1.1757



(a) Hu Men Bridge



(b) Jiang Yin Yangtze Bridge



(c) Fourth Nanjing Yangtze Bridge

Fig. 7 Illustration of the iterative process of flutter safety factor for all suspension bridges considered in this paper using the proposed algorithms: (a) Hu Men Bridge, (b) Jiang Yin Yangtze Bridge and (c) Fourth Nanjing Yangtze Bridge

Table 6 Flutter safety factors for different models

Flutter safety factor	Deterministic model	Random model I($\beta_t = 3.0$)	Random model II($\beta_t = 3.2$)	Random model III($\beta_t = 3.4$)
γ	1.5943	1.2431	1.1739	1.1084

4.4 Parametric study

A parametric study was conducted to investigate how parameter uncertainty, different initial values of γ, mean value of random variables and coefficients of variation of random variables affect the flutter safety factor of suspension bridges. For simplicity, only Jiang Yin Yangtze Bridge with Method I in the previous section is considered.

4.4.1 Effect of parameter uncertainty

One deterministic model where the safety factors are defined as $K = \mu_{V_{cr}} / \mu_{G_s} V_d$ (Ge *et al*. 2003a) (V_d is the bridge standard design wind speed with 100 year return period) and three random models associated with different target reliability indexes are used to investigate the effect of parameter uncertainty on flutter safety factor, γ. Three different values of the target reliability index are used: 3.0, 3.2 and 3.4. The flutter safety factors are given in Table 6 for different models. It can be seen from Table 6 that (1) the flutter safety factors from all random models are smaller than those from deterministic model, indicating that parameter uncertainty affects the flutter safety factors. In other words, neglecting the parameter uncertainties results in a significant overestimation of the flutter safety factor; (2) As the target reliability index increases, the estimated flutter safety factor decreases; (3) The deterministic method gives higher flutter safety factor of suspension bridges because of neglecting the parameter uncertainty effects. For accurate flutter safety factor, it is necessary that the analysis technique incorporate the effect of structural parameters randomness. This is of special importance for accurate estimation of flutter safety factor of suspension bridges, which exhibit wide dispersion in structural parameters. This problem can be solved by the proposed method. The proposed method does offer a significant improvement over the deterministic method.

4.4.2 Effect of different initial values of γ

Since the initial value of γ used in the proposed method is chosen arbitrarily, it is necessary to investigate the effect of initial value of γ on the estimated flutter safety factor. For this purpose, three different initial values of γ are used: 1.5, 2.5 and 3.5. The variations of the flutter safety factor with the iteration number are shown in Fig. 8 for different initial values of γ. It can be seen that the iteration number increases as the difference between the initial and accurate values of γ increases. However, convergence and accuracy are achieved regardless of the initial value of γ. The results indicate that the initial value of γ could have a major effect on the rate of convergence of the proposed algorithm. The accuracy of the proposed algorithm is not influenced by the initial value of γ. Therefore, the proposed algorithm can be used to estimate the flutter safety factor of suspension bridges when target reliability level is specified for the limit state considered in the design.

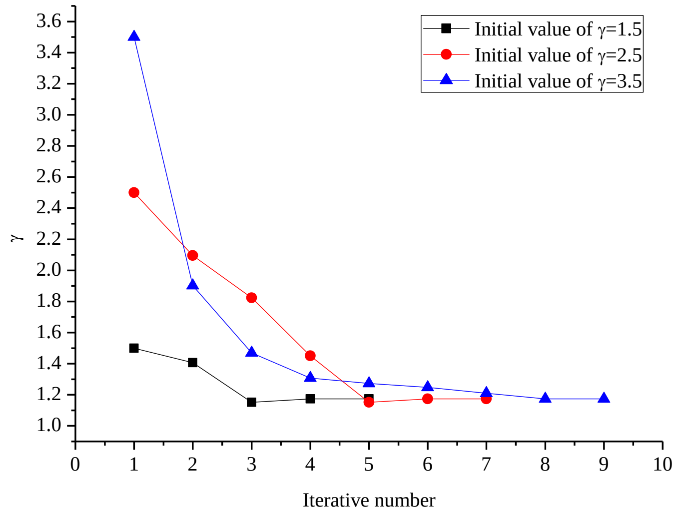
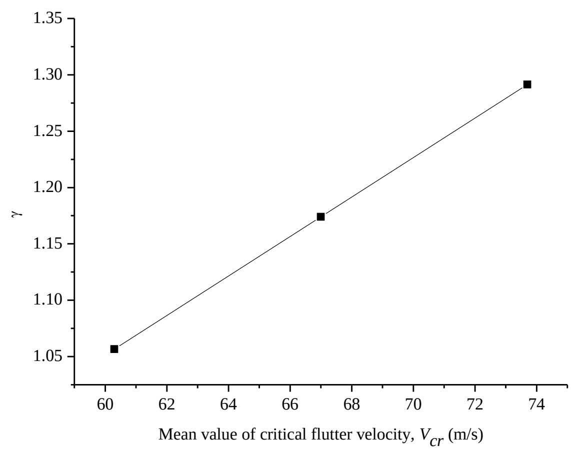


Fig. 8 Variations of flutter safety factors versus the number of iterations for different initial value of γ

4.4.3 Effect of mean value of random variables

Keeping the coefficients of all random variables unchanged, only the mean value of all random variables varies, and the estimated flutter safety factors are compared in Fig. 9. As the mean values of random variables V_{cr} and C_w increase, the estimated flutter safety factors increase. However, an opposite effect is observed for the random variables G_s and V_b. As the mean value of the random variables G_s and V_b increase, the estimated flutter safety factors decrease.



(a)

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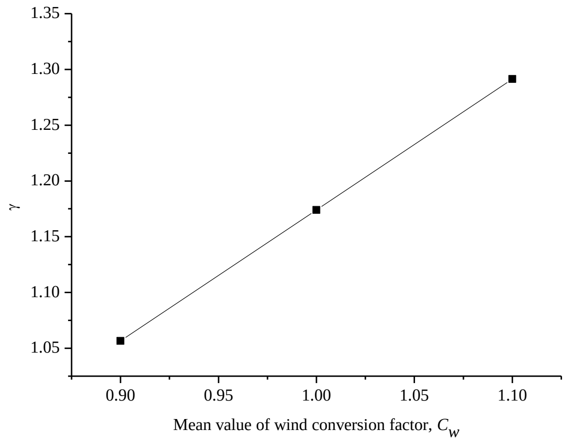

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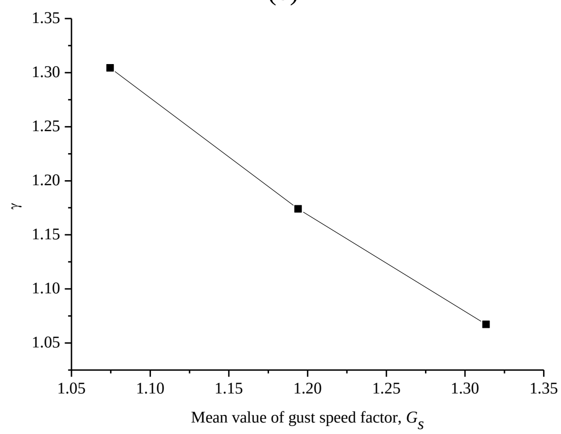

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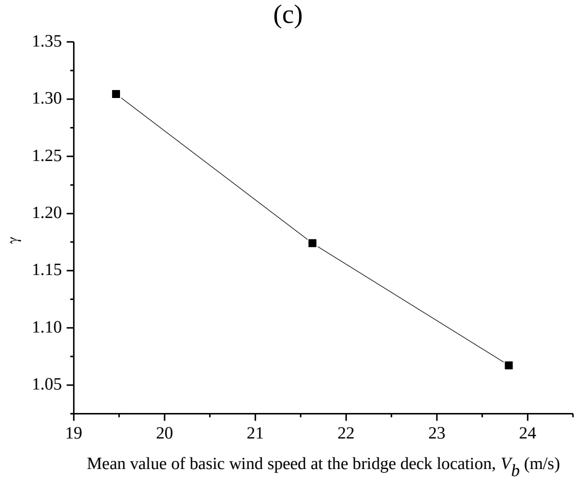
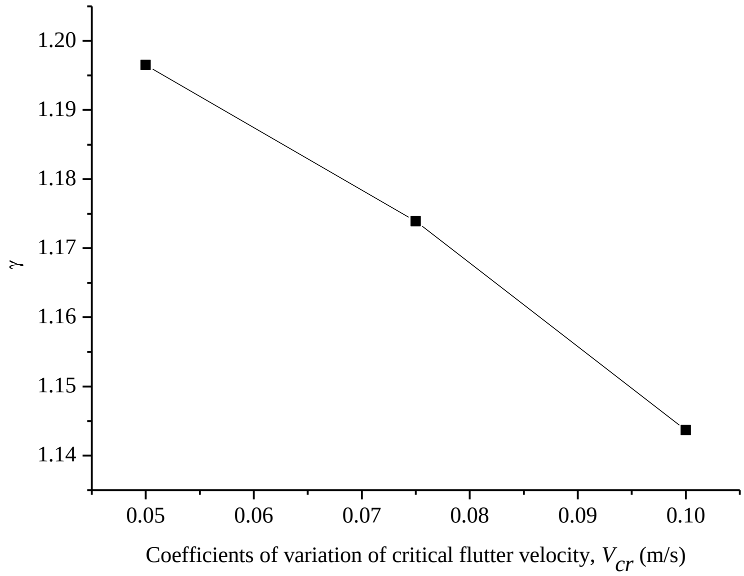


(d)

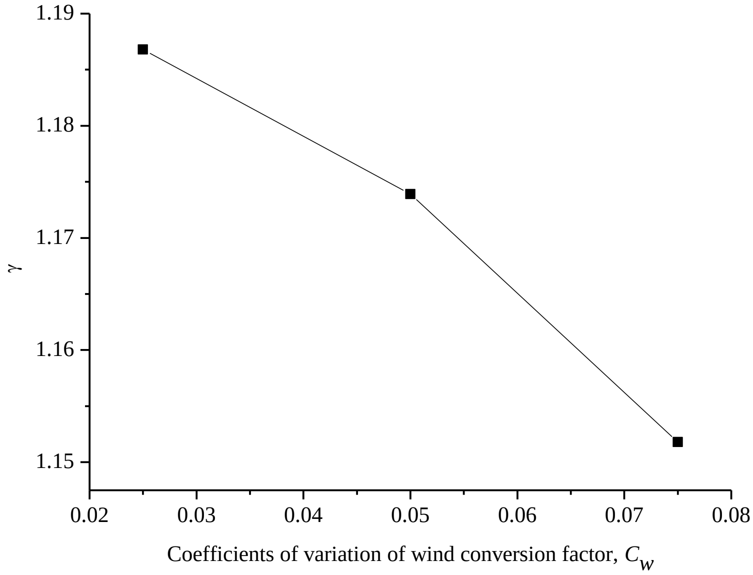
Fig. 9 Influence of the mean values of the different random variables on the flutter safety factors: (a) critical flutter speed, (b) conversion factor, (c) gust speed factor and (d) basic wind speed at the bridge deck location

4.4.4 Effects of coefficients of variation of random variables

By changing the coefficients of variation of random variables, the flutter safety factor is computed using the Method I described previously. The results are plotted in Fig. 10. It can be seen that the estimated flutter safety factors decrease as the coefficients of variations of random variables increase.

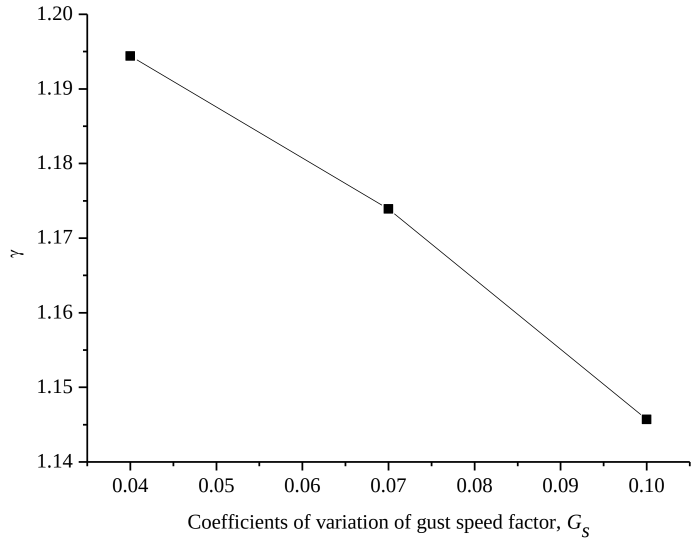


(a)

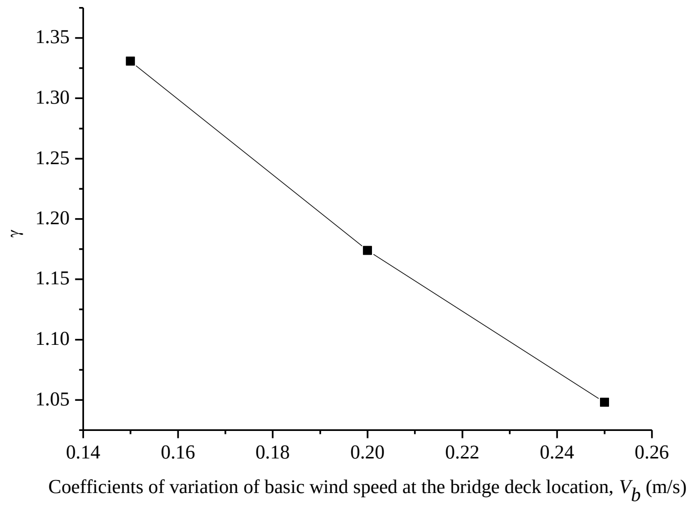


(b)

Continued-



(c)



(d)

Fig. 10 Influence of the coefficients of variation of the different random variables on the flutter safety factor: (a) flutter critical speed, (b) conversion factor, (c) gust speed factor and (d) basic wind speed at the bridge deck location

5. Conclusions

An efficient and accurate method has been proposed to estimate flutter safety factor of suspension bridges satisfying prescribed reliability levels. Uncertainties which arise from the basic wind speed at the bridge deck location, critical flutter velocity, the wind conversion factor from a scaled model to the prototype structure and the gust speed factor have been incorporated. The proposed method integrates the concepts of the inverse reliability method and the calculation method of the critical flutter velocity of suspension bridges. The three versions of the proposed method (Method I, Method II and Method III) are compared.

As the applications of the proposed method, the flutter safety factors of three long span suspension bridges are estimated. The effects of various parameters on the estimated flutter safety factor of suspension bridges are investigated, and the following conclusions can be drawn:

- The validity and the accuracy of the proposed method are verified by the forward reliability analysis. Therefore, the proposed method would be effective in estimating flutter safety factors of suspension bridges satisfying prescribed reliability levels.
- Neglecting the parameter uncertainty effects results in a significant overestimation of the flutter safety factor of suspension bridges. The actual flutter safety factor of suspension bridges should be estimated based on the proposed method.
- The target reliability index has a significant influence on the flutter safety factor of suspension bridges. As the target reliability index increases, the estimated flutter safety factor decreases.
- The initial value of flutter safety factor could have a major effect on the rate of convergence of the proposed method. The iteration number increases as the difference between the initial and accurate values of flutter safety factor increases. However, the accuracy of the proposed method is not influenced by the initial value for flutter safety factor. Therefore, the proposed method can be used to estimate the flutter safety factor of suspension bridges when target reliability level is specified for the limit state considered in the design.
- The flutter safety factor of suspension bridges is highly influenced by the statistics of some random variables such as the basic wind speed at the bridge deck location, V_b, the critical flutter velocity, V_{cr}, the wind conversion factor from a scaled model to the prototype structure, C_w and the gust speed factor, G_s. Therefore, the accurate determination of the distribution of such parameters is very important to obtain reliable estimation results.

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