J. Wind Eng. Ind. Aerodyn. 135 (2014) 149–162

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Reliability based design optimization of long-span bridges considering flutter

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ARTICLE INFO

Keywords:
RBDO
Optimization
Reliability
Flutter
Flutter derivatives
Uncertainty
Limit state function

ABSTRACT

Three reliability based design optimization methods, namely reliability index approach, performance measure approach and sequential optimization and reliability assessment are applied to a long-span suspension bridge under probabilistic flutter constraint. Uncertainties in extreme wind velocity as well as flutter derivatives obtained in wind tunnel are considered. The RBDO problem presented in this research seeks to minimize the bridge girder weight by varying the thicknesses of the girder plate while satisfying the structural reliability level under flutter. In order to solve this problem, the three RBDO methods mentioned above were programmed in Matlab code, which calls Abaqus finite element models to obtain structural responses and FLAS code, developed by our research group, to calculate flutter velocity. The proposed Messina Bridge was used as an application example of these methods. Prior to solve the RBDO problem, reliability analyses were performed in order to obtain the safety level of the original design. The results obtained by different RBDO methods are then compared for their accuracy and computational efficiency.

1. Introduction

As the span length of cable supported bridges increases along with technological advances, the bridge structure becomes more flexible and more prone to flutter. Flutter is an important aeroelastic instability that wind forces acting on the bridge deck combined with the deck movement itself cause negative net damping and increase the deck movement exponentially until its material failure. For a large structure such as a long-span bridge, it is important to seek safety against flutter while minimizing the cost.

Many researchers have worked on reliability analyses of bridge flutter. Ostenfeld-Rosenthal et al. (1992) considered flutter velocities obtained in wind tunnel as a Gaussian random variable affected by two other random variables. In this research the extreme wind speed follows a Gumbel distribution and the First Order Reliability Method (FORM) is performed with a total number of four random variables. Ge et al. (2000) presented a method to obtain probability of failure due to flutter using FORM. In this research four random variables were considered and an empirical flutter speed formula was used to define the limit state function. Pourzeynali and Datta (2002) considered uncertainty in flutter derivatives employing a model with two degrees of freedom of lift and moment. Analytical formulas of six flutter derivatives were employed in their research. Cheng et al. (2005) presented a reliability flutter study with fourteen random variables using FORM method. The authors approximated the limit state function by the response surface method. Baldomir et al. (2013) considered flutter derivatives, extreme wind velocity as well as structural damping as random variables and performed reliability analyses of a long-span bridge using FORM. Their formulation was applied to the proposed Messina Bridge.

As compared to traditional deterministic optimizations, reliability based design optimization (RBDO) performs structural optimization considering system uncertainties to minimize structural weight while satisfying a predetermined structural safety level. The uncertainties are taken into account as a form of random variables that constitute probabilistic constraints, which are evaluated in the reliability routine. Therefore, the RBDO can provide more precise and competitive solution to an optimization problem than a deterministic optimization.

The RBDO formulations can be grouped into three major categories depending on the arrangement of design optimization and reliability routines, namely two-level, mono-level and decoupled methods. The most direct approach to solve a RBDO problem may be the two-level method, in which the design optimization is performed in the outer loop while the reliability analysis is carried out in the inner loop. Two of the most commonly used approaches in this category are Reliability Index Approach (RIA) and Performance Measure Approach (PMA).

The RIA method was proposed by Nikolaidis and Burdisso (1988) applying the concept of Hasofer and Lind (1974) to expand the limit state function at Most Probable Point of failure (MPP),

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http://dx.doi.org/10.1016/j.jweia.2014.10.006
0167-6105/

which can be evaluated by iterative methods. However, the method presented drawbacks of high computational cost and slow convergence. The PMA method was introduced by Tu and Choi (1999) to overcome these disadvantages. The reliability measure was converted into performance measure by solving inverse reliability problem, which seeks the minimum performance function on the reliability surface. The method arises from an idea that optimizing a complex objective function under simple constraint functions is much easier than optimizing a simple objective function under complex constraint functions (Aoues and Chateauneuf, 2010). In fact, according to researchers as Lee et al. (2002) and Youn et al. (2003), PMA was found to be more computationally efficient and numerically stable than RIA.

Many researchers seek for alternative more efficient RBDO formulations to avoid computationally intensive nested optimization problems. The method called the Sequential Optimization and Reliability Assessment (SORA) introduced by Du and Chen (2004) is one of the most promising approaches in this category. The main idea of SORA is to reformulate the RBDO problem into a sequence of deterministic optimization and reliability analysis. It evaluates the constraint at the MPP by inverse reliability analysis to check if a given design point meets the required reliability level. The method is shown to be computationally efficient; however, according to Ramu et al. (2006) it does not always guarantee to lead to an optimal design.

In the past years, many researchers have worked on the RBDO applied to different structures. Kaushik (2007) applied the RBDO to automobile crashworthiness, while Karadeniz et al. (2009) utilized this discipline to the design of offshore towers. Spence and Gioffrè (2011) and Huang et al. (2012) applied the RBDO to full scale wind excited structures such as tall buildings where the excitation is derived from experimental wind tunnel data. Frangopol and Maute (2003) presented an overview of the life-cycle RBDO applied to civil and aerospace structures.

Although there have been many works of RBDO applied to structures, there has been no research on RBDO of long-span bridges considering probabilistic flutter constraint. In this paper, an application of the RBDO methods is presented in order to minimize the girder weight of a long-span bridge by imposing a structural reliability level under flutter. This approach was applied to the Messina Bridge in Italy using 3 different methods of RIA, PMA and SORA.

In summary, the contribution of this paper is as follows:

- Application of three RBDO methods, namely RIA, PMA and SORA on a long-span suspension bridge considering probabilistic flutter constraint. The experimentally obtained flutter derivatives and extreme wind velocity are considered as random variables while the plate thicknesses of bridge girder are defined as design variables. The methods search for the optimum design to minimize the girder weight while satisfying the required safety level under flutter as well as other deterministic constraints.
- Application of the above formulation to the proposed Messina Bridge.
- Comparison of computational efficiency and numerical stability among these three methods.

2. Flutter analysis of long-span bridges by hybrid method

Flutter speed of a long-span bridge may be calculated using a hybrid method that consists of an experimental phase of testing a sectional model of a bridge deck in a wind tunnel and a subsequent computational phase (Jurado and Hernandez, 2004).

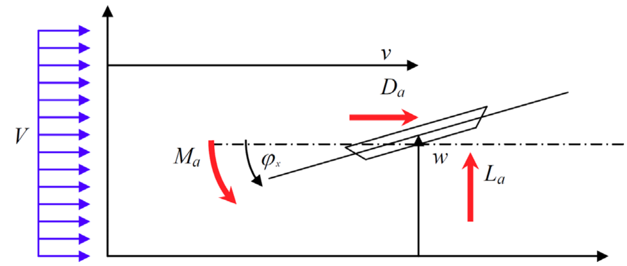

Fig. 1. Sign convention for flutter analysis.

A vibrating bridge deck under wind flow creates self-induced forces that depend on displacement vector $\mathbf{y} = (v, w, \varphi_x)^T$ and its derivative, where v is horizontal, w is vertical and φ_x is the rotational degrees of freedom of the deck as shown in Fig. 1.

The relationship between aeroelastic force, $\mathbf{f}_a$ and the displacement vector can be written employing a set of eighteen functions called flutter derivatives as formulated by Scanlan and Simiu (1986).

$$\mathbf{f}_a = \begin{Bmatrix} D_a \\ L_a \\ M_a \end{Bmatrix} = \frac{1}{2}\rho V K B \times \begin{pmatrix} P_1^* & -P_5^* & -BP_2^* \\ -H_5^* & H_1^* & BH_2^* \\ -BA_5^* & BA_1^* & B^2A_2^* \end{pmatrix} \begin{Bmatrix} \dot{v} \\ \dot{w} \\ \dot{\varphi}_x \end{Bmatrix} + \frac{1}{2}\rho V^2 K^2 \times \begin{pmatrix} P_4^* & -P_6^* & -BP_3^* \\ -H_6^* & H_4^* & BH_3^* \\ -BA_6^* & BA_4^* & B^2A_3^* \end{pmatrix} \begin{Bmatrix} v \\ w \\ \varphi_x \end{Bmatrix} \quad (1)$$

where B is the deck width, ρ is the air density, V is the acting wind speed, $K = B\omega/V$ is the reduced frequency with ω as the response frequency,A_i^*, H_i^* and P_i^* $(i = 1,\ldots,6)$ are the flutter derivatives obtained experimentally.

The multimodal flutter analysis is used to solve this problem. This well-known method can be found in papers such as Katsuchi et al. (1999), Chen et al. (2001) and Jurado et al. (2011).

Eq. (1) can be expressed in a matrix form as:

$$\mathbf{f}_a = \mathbf{C}_a\dot{\mathbf{y}} + \mathbf{K}_a\mathbf{y} \quad (2)$$

where $\mathbf{K}_a$ and $\mathbf{C}_a$ are aeroelastic stiffness and damping matrix, while $\mathbf{y}$ represents a displacement vector of a node along the deck. The matrix, $\mathbf{K}_a$ and $\mathbf{C}_a$ for the entire bridge can be obtained by assembling the matrix of each bar element of the deck. The dimension of the matrices coincides with the total number of degree of freedom of the bridge deck.

The system of equations that governs the dynamic behavior of the deck under aeroelastic forces is expressed as:

$$M\ddot{\mathbf{y}} + C\dot{\mathbf{y}} + \mathbf{K}\mathbf{y} = \mathbf{f}_a \quad (3)$$

where $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ are mass, damping, and stiffness matrices. By combining (2) and (3), we get:

$$M\ddot{\mathbf{y}} + (\mathbf{C} - \mathbf{C}_a)\dot{\mathbf{y}} + (\mathbf{K} - \mathbf{K}_a)\mathbf{y} = \mathbf{0} \quad (4)$$

In order to solve the problem of Eq. (4), a modal analysis is performed. The displacement vector can be written as a function of the most relevant m mode shapes grouped by a modal matrix, $\mathbf{\Phi}$.

$$\mathbf{y} = \mathbf{\Phi} w e^{\mu t} \quad (5)$$

where μ and $\mathbf{w}$ are complex values. By plugging (5) into (4), the system is transformed to:

$$(\mu^2\mathbf{I}\mathbf{w} + \mu\mathbf{C}_R\mathbf{w} + \mathbf{K}_R\mathbf{w})e^{\mu t} = \mathbf{0} \quad (6)$$