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Framework for sensitivity and uncertainty quantification in the flutter assessment of bridges

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ABSTRACT

The phenomenon of aerodynamic instability caused by wind is usually a major design criterion for long-span cable-supported bridges. If the wind speed exceeds the critical flutter speed of the bridge, this constitutes an Ultimate Limit State. The prediction of the flutter boundary therefore requires accurate and robust models. The state-of-the-art theory concerning determination of the flutter stability limit is presented. Usually bridge decks are bluff and therefore the aeroelastic forces under wind action have to be experimentally evaluated in wind tunnels or numerically computed through Computational Fluid Dynamics (CFD) simulations. The self-excited forces are modelled using aerodynamic derivatives obtained through CFD forced vibration simulations on a section model. The two-degree-of-freedom flutter limit is computed by solving the Eigenvalue problem.

A probabilistic flutter analysis utilizing a meta-modelling technique is used to evaluate the effect of parameter uncertainty. A bridge section is numerically modelled in the CFD simulations. Here flutter derivatives are considered as random variables. A methodology for carrying out sensitivity analysis of the flutter phenomenon is developed. The sensitivity with respect to the uncertainty of flutter derivatives and structural parameters is considered by taking into account the probability distribution of the flutter limit. A significant influence on the flutter limit is found by including uncertainties of the flutter derivatives due to different interpretations of scatter in the CFD simulations. The results indicate that the proposed probabilistic flutter analysis provides extended information concerning the accuracy in the prediction of flutter limits.

The final aim is to set up a method to estimate the flutter limit with probabilistic input parameters. Such a tool could be useful for bridge engineers at early design stages. This study shows the difficulties in this regard which have to be overcome but also highlights some interesting and promising results.

1. Introduction

The study of aeroelastic behaviour is very important for the design and analysis of long-span cable-supported bridges. The exceptional length and slenderness of these structures make them highly susceptible to wind actions. Therefore, robust and accurate prediction models are required to avoid potential collapse of the bridge due to flutter instability. The interaction of the aerodynamic forces and the structural motion can lead to instability when the energy input from the wind flow exceeds that dissipated by the structural damping. The coupling of torsional and bending mode occurs and the amplitude of the motion progressively increases at this stage which is known as 'classical flutter'. The negative aerodynamic damping is produced such that the deformations reach a level at which failure happens. The main objective of studying flutter phenomena is to find the instability limit which is also known as 'flutter limit' and making sure that this wind speed is not exceeded during the design life of the bridge with a certain probability.

Wind tunnel tests are commonly used to study wind action on bridges. Such tests are expensive and time consuming. Therefore, analytical and numerical methods are used at preliminary stages. Theodorsen [1] developed a theory to build the self-excited forces for airfoils based on potential flow past a flat plate by using circulation functions. Scanlan and Tomko [2] gave a popular linearized form to represent the self-excited forces by using the so-called 'aerodynamic derivatives' or 'flutter derivatives'. This representation has been commonly used for the aeroelastic instability problems due to its ability to describe the motion-induced forces of arbitrary section geometries. Free vibration [3] or forced vibration [4] approaches are used to extract the aerodynamic derivatives. Walther and Larsen used *Computational Fluid Dynamics* (CFD) to compute flutter derivatives numerically [4,5]. The analytical solutions for the two-degree-of-freedom aeroelastic

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instability include Eigenvalue analysis [6]. Ge and Xiang [7] used two-dimensional and three-dimensional analysis methods to determine flutter stability of long-span bridges.

The role of uncertainty of input parameters on bridge flutter has received significant attention. Jakobsen and Tanaka [8] investigated the modelling uncertainties and a possible refinement of the description of wind loading and wind–structure interaction from the literature surveys. Cheng and Xiao [9] used response surface method for the probabilistic free vibration and flutter analyses of suspension bridges. An analytical sensitivity analysis of the flutter phenomenon in long-span bridges was presented by Jurado and Hernández [10]. Kwon [11] presented a numerical procedure for evaluating the uncertainty that arises during model design and wind tunnel tests whereas Seo [12] discussed the development and implementation of a methodology for the buffeting response of cable-supported bridges, including uncertainty in the flutter derivatives. Mannini and Bartoli [13] investigated flutter instability in a probabilistic way and the effect of correlation between flutter derivatives in the definition of the probability distribution of the flutter wind speed.

In this paper the study is made on the aeroelastic phenomena of flutter and respective analyses are performed for bridges by using the deterministic and probabilistic approaches. These approaches are used on two bridge cross sections to calculate their critical flutter limits. The main objective of this study is to create a framework for probabilistic flutter analysis. The approach demonstrates how to take parameter uncertainty into account according to the importance of each parameter by performing sensitivity analysis.

2. Flutter phenomenon

Flutter is a coupling of aerodynamic forcing with a structural dynamics problem. In this study, analytical and numerical approaches are coupled to calculate the flutter limit from the hybrid model. The flutter analysis is performed by complex Eigenvalue solution. Models for aerodynamic forces employed are the analytical Theodorsen expressions for the motion-induced aerodynamic forces of a flat plate and Scanlan derivatives of a bridge section as a Meta-model. The CFD simulations using the *Vortex Particle Method* (VPM) are used to compute such aerodynamic derivatives. The structural representation is dimensionally reduced to a two-degree-of-freedom section model calibrated from an arbitrary complex three-dimensional global model. Thus derived and analysed models are

(a) Fully Analytical (Model#1).
(b) Derivative-based Eigenvalue Analysis (Model#2).

The relevant pairs of vertical and torsional modes of the bridge deck are considered for the flutter analysis. The important factors which may affect the flutter limit are the degree of shape-wise similarity and the frequency separation between the two modes. For simplicity, linear viscous damping is considered and the same structural damping ratio is assumed for all modes.

A simplified two-degree-of-freedom representation of the bridge deck may be considered as shown in Fig. 1 where U_∞ is the wind speed and B is the width of the section. The equations of motion can be written as:

$$m\ddot{h} + 2m\xi_h\omega_h\dot{h} + m\omega_h^2 h = F_L, \quad (1)$$

$$I\ddot{\alpha} + 2I\xi_\alpha\omega_\alpha\dot{\alpha} + I\omega_\alpha^2\alpha = F_M \quad (2)$$

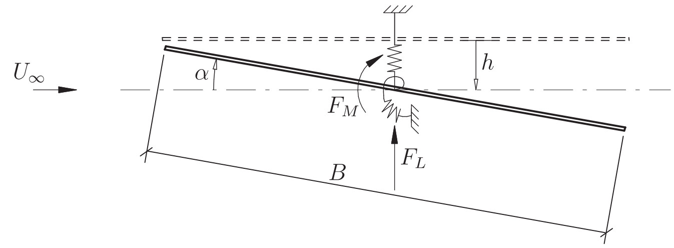

Fig. 1. Definition of degrees-of-freedom (heave h and pitch α) for flutter analysis: (dash) undeformed, and (solid) deformed [14].

where m and I are the mass and mass moment of inertia, respectively, ξ_h, ξ_α are the damping ratios and ω_h and ω_α are the natural circular frequencies for the heave and pitch modes, respectively, h and α are the vertical displacement and rotation, respectively, F_L and F_M are the lift force and moment, respectively.

Scanlan [2] expressed the motion-induced aerodynamic forces on a cross section as a meta-model which assumes that the self-excited lift F_L and moment F_M for a bluff body may be treated as linear in displacement h and rotation α and their first derivatives. In a linearized form:

$$F_L = \frac{1}{2}\rho U_\infty^2 B\left[KH_1^*\frac{\dot{h}}{U_\infty} + KH_2^*\frac{B\dot{\alpha}}{U_\infty} + K^2H_3^*\alpha + K^2H_4^*\frac{h}{B}\right], \quad (3)$$

$$F_M = \frac{1}{2}\rho U_\infty^2 B^2\left[KA_1^*\frac{\dot{h}}{U_\infty} + KA_2^*\frac{B\dot{\alpha}}{U_\infty} + K^2A_3^*\alpha + K^2A_4^*\frac{h}{B}\right] \quad (4)$$

with

$$K = \frac{B\omega}{U_\infty} \quad (5)$$

where ρ is the air density, H_i^* and A_i^* $(i = 1, \ldots, 4)$ are the non-dimensional functions of K known as aerodynamic derivatives which are associated with self-excited lift and moment, respectively. K is the reduced frequency and ω is the frequency of the bridge oscillation under aerodynamic forcing. These aerodynamic derivatives are usually measured in special wind tunnel tests but can also be computed from CFD simulations.

2.1. Coupled global models for flutter analysis

2.1.1. Fully analytical (Model#1)

Fully analytical models are simple, easy to implement and allow a better insight into the force coupling. Theodorsen investigated the flutter phenomenon for aircraft wings and gave a very popular closed-form solution for the self-excited forces [1]. It considers a flat plate subjected to the action of a smooth oncoming flow (see Fig. 1). The plate is assumed to have two-degrees-of-freedom only i.e. in heave and pitch directions. The theoretical expressions on a flat plate airfoil for sinusoidal oscillating lift F_L and moment F_M are as follows:

$$F_L = -\rho b^2 U_\infty \pi\dot{\alpha} - \rho b^2\pi\ddot{h} - 2\pi\rho C U_\infty^2 b\alpha - 2\pi\rho C U_\infty b\dot{h} - 2\pi\rho C U_\infty b^2\frac{1}{2}\dot{\alpha}, \quad (6)$$

$$F_M = -\rho b^2\pi\frac{1}{2}U_\infty b\dot{\alpha} - \rho b^4\pi\frac{1}{8}\ddot{\alpha} + 2\rho U_\infty b^2\pi\frac{1}{2}C U_\infty\alpha + 2\rho U_\infty b^2\pi C\dot{h} + 2\rho\frac{1}{2}U_\infty b^3\pi C\dot{\alpha} \quad (7)$$

with