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Aerodynamic uncertainty propagation in bridge flutter analysis

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ABSTRACT

This paper presents a method to approach flutter instability in a probabilistic way and to calculate the critical wind speed, starting from the probability distribution of the flutter derivatives. Uncertainty propagation is studied and the results can be used for risk-assessment purposes. The statistical properties of experimental flutter derivatives were investigated with ad hoc wind tunnel tests performed on a bridge deck model of common geometry. The probability distribution of the flutter critical wind speed can be analytically calculated if a simplified approach to flutter is followed, while Monte Carlo methods have to be utilized in the general case. Several application examples are presented and both well-behaving and particularly critical cases of uncertainty propagation are discussed. Finally, the effect of partial correlation between flutter derivatives is studied and its non-negligible role in the definition of the probability distribution of the flutter wind speed is underscored.

1. Introduction

Large and flexible structures, such as long-span bridges, are very sensitive to wind action, which influences and often determines their design from the very early stages. The magnitude of the structural response to turbulent wind (buffeting), the sensitivity to vortex-induced vibration and the safety margin with respect to aeroelastic instabilities such as flutter have to be carefully quantified and wind tunnel testing is, and probably will still remain for a long time, the main tool of analysis.

In particular, classical flutter is a dynamic instability due to self-excitation that involves (mainly) a vertical bending and a torsional mode, leading to large-amplitude oscillations which indefinitely grow with the wind speed. Torsional flutter (or torsional galloping) is also relevant for bridge structures, wherein negative damping in a torsional mode can be attained without any coupling with other modes.

The improvement of state-of-the-art knowledge of bridge aerodynamics and aeroelasticity has progressively underscored the importance of uncertainty quantification in the assessment of wind-resistant design of these structures. A framework for performance-based wind engineering has also been recently outlined [1]. In the bridge flutter problem, beside the intrinsic aleatory nature of wind hazard and the epistemic uncertainty due to the imperfection of the mathematical models, additional uncertainty is associated with the parameters of the selected model. In fact, several dynamic parameters are not precisely known: in particular, while mass, mass moment of inertia, natural frequencies and deck dimensions are often sufficiently well defined, very rough estimates for structural damping are usually employed in the calculations, despite its leading role in the definition of the response to dynamic loads or vortex-induced vibration and its importance in certain types of flutter instability [2–4]. Another source of uncertainty is represented by the non-negligible dispersion of the wind tunnel measurements of aerodynamic coefficients. In particular, this is the case of the flutter derivatives, necessary for flutter and buffeting analyses of bridge decks [5–7]. Such functions are usually treated as if they were deterministic but several studies demonstrated the random nature of the experimental results both in case of free- [8–10] and forced-vibration [11] measurement methods.

In the literature there are several attempts to include flutter instability in bridge reliability analyses [12–15] but only in few cases has the uncertainty in the flutter derivatives been considered, usually assuming a priori a normal or lognormal probability distribution with a postulated value of the standard deviation. The effect of the variability of flutter derivatives was investigated by Bartoli et al. [16], who interpolated the measured derivative values with polynomial functions and then artificially varied the coefficients by ± 15%, obtaining non-negligible differences in the flutter critical wind speed. A similar approach was followed for the buffeting response by Caracoglia [10], who observed that the variation of the output was relatively small with respect to that imposed to the input. Caracoglia et al. [17] employed the sets of flutter derivatives measured for several bridge sections by different laboratories and with different techniques, collected in [11], and studied the

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variability of the critical wind speed. A similar approach was followed also by the Writers in [9,18], considering data for some bridges of similar cross-section geometries. Later, Seo and Caracoglia [19] proposed a method to numerically evaluate the probability of failure of a bridge prone to torsional flutter considering the uncertainty in two flutter derivatives, treated as independent random variables and approximated with second-order polynomial curves. Their randomness was assumed by comparing sets of measurements by different laboratories and with different techniques or for different mean angles of attack. Another group of works tried to include in the flutter model free-stream turbulence as a parametric random perturbation, studying its effect on the (aleatory) flutter boundary (e.g. [20–22]).

In this paper the epistemic uncertainty of experimental flutter derivatives is investigated by means of wind tunnel tests specifically conceived for this purpose in the case of a bridge deck model of common geometry. With respect to previous works (e.g. [11]), in this case the variability due to different experimental environments and techniques is excluded and only the randomness due to measurement errors and identification procedures is retained. The aim is to gather information on the statistical properties of measured aeroelastic coefficients, although necessarily geometry- and laboratory-dependent, following the demand clearly coming from the scientific community (e.g. [1,11,19]). Also, a method to calculate the probability distribution of the critical wind speed, starting from that of the flutter derivatives, is proposed. Application examples in different cases are provided and the importance of the results in the framework of a risk analysis is highlighted. Another peculiarity of this work is the investigation of the role played by the correlation coefficient between flutter derivatives.

2. Flutter probability of failure

In order to frame the flutter instability of a bridge structure in a risk analysis, the probability of failure can be calculated as follows:

$$P_{fail} = \int_0^\infty P(F = 1|U^\perp) \cdot g(U^\perp) \cdot dU^\perp \tag{1}$$

where F is a binary random variable which takes value 1 if flutter instability occurs and 0 if it does not, $U^\perp$ is the component of the mean wind speed perpendicular to the longitudinal bridge deck axis, while $g(U^\perp)$ is the probability density function (PDF) of $U^\perp$. This expression for the probability of failure relies on the validity of the "cosine rule", according to which only the component $U^\perp$ of the wind velocity is effective with respect to the instability onset (see e.g. [23]); however, the effect of yaw angle on flutter is still a fairly unexplored issue and would deserve further investigation. $P(F = 1|U^\perp)$ denotes the conditional probability that flutter occurs given a certain wind speed and therefore represents a fragility curve.

Flutter is an unrestricted dynamic instability characterized by a certain velocity threshold beyond which the structure is always unstable. Therefore, it holds that $P(F = 1|U^\perp) = P(F = 1|u \leqslant U^\perp) = P(U_{cr} \leqslant U^\perp)$, where U_{cr} is the flutter critical wind speed and $P(U_{cr} \leqslant U^\perp)$ the cumulative probability distribution function (CDF) of the flutter critical wind speed.

This paper proposes a method to calculate the probability distribution $P(U_{cr} \leqslant U^\perp)$, given random structural and aerodynamic input parameters (e.g. flutter derivatives); therefore, as compared to a complete flutter reliability analysis, it is concentrated on the structural vulnerability term only. However, once the hazard term $g(U^\perp)$ is available, the probability of failure of the structure due to flutter can be easily determined through Eq. (1). The calculation of $P(U_{cr} \leqslant U^\perp)$ is performed on the basis of the well-known Scanlan's model of flutter (Section 3), which is inherently deterministic, but assuming uncertain parameters. Finally, in order to better emphasize the effect of uncertainty in the aerodynamic input of the flutter problem, only the aeroelastic coefficients are considered as random variables whilst all the structural parameters are assumed as deterministic quantities. The method reported in the present paper can also be seen as a tile of the complex procedure of performance-based design [1], where the performances of the structure within a probabilistic context are assumed as key objectives of the design.

3. Mathematical model

Classically, the mechanical system can be described by a two-degree-of-freedom (2-DoF) linear oscillator, free to vibrate in heaving $h(t)$ and pitching $\alpha(t)$ modes (Fig. 1). For the sake of simplicity the contributions of drag force and streamwise degree of freedom are waived. If the system is supposed to be mechanically uncoupled, the equations of motion can be written as follows:

$$m[\ddot{h} + 2\zeta_h\omega_h\dot{h} + \omega_h^2 h] = L \tag{2}$$

$$I[\ddot{\alpha} + 2\zeta_\alpha\omega_\alpha\dot{\alpha} + \omega_\alpha^2 \alpha] = M \tag{3}$$

where m and I are the mass and mass moment of inertia per unit length, $\omega_h = 2\pi n_h$ and $\omega_\alpha = 2\pi n_\alpha$ the circular frequencies of heaving and pitching modes (in still air), ζ_h and ζ_α the ratio-to-critical damping coefficients, L and M the lift and moment per unit length and the dot denotes derivative with respect to time. Lift and moment can be expressed as the sum of mean, buffeting and self-excited forces but only the latter are supposed to give rise to flutter instability. Assuming perfectly coupled motion, self-excited forces can be expressed in the Scanlan's form [5,6]:

$$L_{se}(t,K) = qB\left[KH_1^*(K)\frac{\dot{h}(t)}{U} + KH_2^*(K)\frac{B\dot{\alpha}(t)}{U} + K^2H_3^*(K)\alpha(t) + K^2H_4^*(K)\frac{h(t)}{B}\right] \tag{4}$$

$$M_{se}(t,K) = qB^2\left[KA_1^*(K)\frac{\dot{h}(t)}{U} + KA_2^*(K)\frac{B\dot{\alpha}(t)}{U} + K^2A_3^*(K)\alpha(t) + K^2A_4^*(K)\frac{h(t)}{B}\right] \tag{5}$$

where $q = \frac{1}{2}\rho U^2$ is the dynamic pressure, U is the mean wind speed, ρ is the air density, B is the bridge deck chord, $K = \omega B/U$ is the reduced frequency of oscillation, ω is the circular frequency of the flutter coupled mode and the functions H_j^* and A_j^* $(j = 1, \ldots, 4)$ are the flutter derivatives, which have to be identified through wind tunnel tests. These aerodynamic coefficients are often expressed as functions of the reduced wind speed $U_R = 2\pi/K$.

The flutter critical condition is determined assuming harmonic vertical bending-torsional coupled motion and searching for a non-trivial solution, which is obtained when the complex determinant of the resulting algebraic system of equations vanishes. This yields

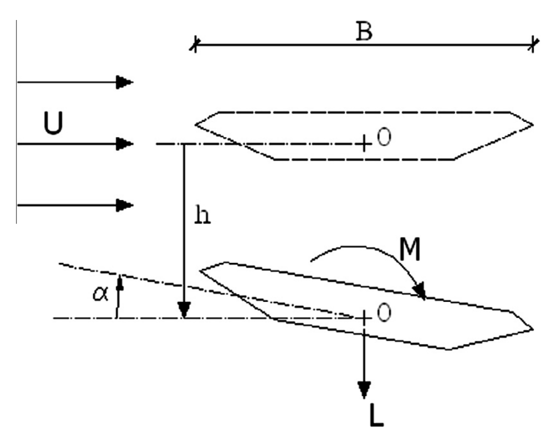

Fig. 1. Reference system for displacements and self-excited forces.