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Monte Carlo analysis of total damping and flutter speed of a long span bridge: Effects of structural and aerodynamic uncertainties

T. Argentini*, A. Pagani, D. Rocchi, A. Zasso

Politecnico di Milano, Department of Mechanical Engineering, via La Masa 1, 20156 Milano, Italy

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ABSTRACT

Monte-Carlo simulations are a well-established methodology to numerically assess the effect of variations of both mechanical and aerodynamic parameters on the aeroelastic stability of a suspended bridge. In this research paper we use this statistical approach to present a design methodology for the assessment of long span aeroelastic behavior that considers not only the flutter velocity as a unique safety index, as it is common practice, but also the trend of the total damping as a function of the wind velocity.

Specifically, several significant in-service conditions are considered. Indeed, wind velocities at in-service conditions are events with a probability much higher than flutter condition, and in these cases a reliability analysis represents an added value in the design process. Therefore the statistical analysis of total damping at in-service conditions is suggested as a useful tool to judge the performance of a structure especially for those structures where the wind–structure interaction represents the capital aspect of the overall design as it happens for the very long span bridges.

Given the probability distribution of the input parameters, the Monte Carlo simulations allows one to statistically investigate the aeroelastic stability of the structure, in terms of range of variation of the total damping and flutter velocity, through an eigenvalue analysis. It is also possible to state the probability of not matching the design technical specification and the probability of being in a certain prescribed variation band.

The mathematical and statistical background of the design methodology are presented and a case of study is analyzed with reference to the Messina Straits Bridge. The test case was chosen to stress the methodology with a challenging design, where extreme structural and aerodynamic solutions are implemented to reach a main span length of 3300 m and where the performances of the structure are deeply bounded to the reliability of the aeroelastic design.

1. Introduction

The continuous progress in knowledge and technology has let engineers design suspension bridges with increasingly longer spans. A major concern for such slender structures is that they suffer from aeroelastic instabilities caused by the self-excited aerodynamic forces acting on the deck. While the risk of torsional divergence can be avoided by a careful aerodynamic design of the deck section, flutter instability still remains a critical aspect that involves both the structural and the aerodynamic characteristic of the bridge: evaluating and predicting the aeroelastic performances of the bridge during construction and *in service* states is therefore a crucial point of its design (e.g. Diana et al., 1995, 2013b; Argentini et al., 2013, 2011; Ge, 2011).

Since the first aeroelastic studies of civil structures, the problem of stability has been studied from a deterministic point of view; nowadays, this approach is the starting point of probabilistic analyses that take into account the uncertainties of the parameters involved. Such an approach is a more powerful design tool, since it supports deterministic results with confidence intervals (e.g. Jakobsen and Tanaka, 2003).

Within this framework, researchers have dealt with the reliability of deterministic flutter prediction for several years (e.g. Bucher and Lin, 1988; Prenninger et al., 1990; Ostenfeld-Rosenthal et al., 1992; Pourzeynail, 2002). The most used and developed approaches are the *First* and the *Second Order Reliability* method (as proposed by Cheng et al., 2005; Ge et al., 2000; Cheng and Li, 2009; Baldomir et al., 2011; Kiureghian, 2005), and the Monte-Carlo method (Bartoli and Mannini, 2005; Mannini and

* Corresponding author.
E-mail address: tommaso.argentini@polimi.it (T. Argentini).

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Bartoli, 2010). The former methods manage the reliability problem considering a linearized objective function, while the latter allows one to numerically obtain the statistical distribution of the target parameter.

All the cited works consider the critical flutter speed as the key parameter of the reliability analysis, however the critical flutter speed is not a unique index for the assessment of the safety of the structure against wind loads. Besides the flutter speed, the trend of the total damping of the structure (ζ_{tot}) as a function of the mean wind velocity is a complementary safety index that allows one to assess the aeroelastic behavior of a bridge over a wide range of operating conditions.

As a matter of fact, the critical wind speed ($V_{flutter}$) is in general larger than the maximum wind speed the structure is expected to withstand in its life period, that is called design velocity (V_{design}). This wind speed has a large return period (or a low probability of occurrence): usually, the structure faces wind speeds that are lower than the design speed and with a shorter return period. Thus it is important to assess the safety of a bridge also for wind velocities that are more probable than the design velocity.

To this end, the total damping of the structure (intended as the sum of the structural and aerodynamic damping, $\zeta_{tot}=\zeta_{aero}+\zeta_{str}$) is a relevant safety index. Therefore, the uncertainties on the aeroelastic stability of the structure should be investigated not only at extreme conditions, but also in the operating ones. In order to do this, in this paper, the probabilistic study of the flutter speed is complemented with a probabilistic analysis of the total damping of the bridge for several operating wind velocities.

To better explain why the trend of total damping is an important safety index, we propose the following example in which we compare two different design solutions having the same critical flutter speed, but very different performance at typical *in-service* conditions, as qualitatively sketched in Fig. 1.

For the considered example, two solutions (named A and B) show the typical trends of the total damping parameter that, starting from the structural value (ζ_{str}) in still air, initially increase their value up to a maximum, and then they reverse their slope until the total damping becomes negative (at $V/V_{flutter}=1$).

If the aerodynamic design is correctly performed, the total damping (ζ_{tot}) should be sufficiently large in all the wind speed range. With reference to Fig. 1, the total damping ζ_{tot} for Solution B is large only in the lower range of wind velocity (around $\frac{V}{V_{flutter}}=0.2$), and then it decreases up to instability. It is important to have larger values of ζ_{tot} also at high wind speed, as shown by Solution A, in order to have a sufficient safety margin also in the presence of uncertainties on design parameters to prevent undesired instability problem.

The way the Messina Project Technical Specifications deals with the problem is to prescribe minimum threshold for the ζ_{tot} parameters in the range of wind speed from 0 to V_{design}, shown by the rectangular boundaries in Fig. 1. The higher minimum value in the first range is representative of the requirements for a limited buffeting bridge response due to the unsteady turbulent wind conditions. The second limit asks that aerodynamic effects keep on adding dissipation to the structure up to the design speed.

All these considerations make the total damping ζ_{tot} a relevant design index for the safety of the bridge, when aeroelastic effects are present. That is why the propagation of uncertainties and its statistical analysis have to be extended to the total damping instead of referring only to the critical flutter speed, as traditionally done.

With this purpose, the objective of this research paper is to present a methodology to assess the uncertainty of ζ_{tot} in order to evaluate whether possible mismatches between design parameters and actual ones do impact in a critical way on the evolution of the aeroelastic behavior of the structure.

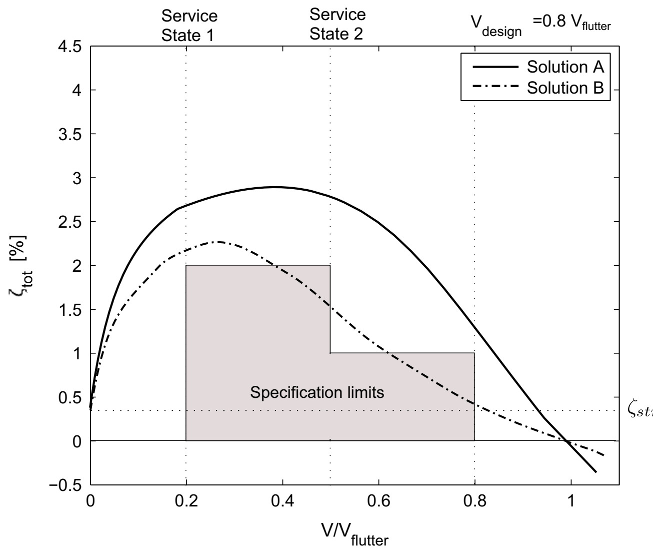

Fig. 1. Total damping as a function of the wind speed (in non-dimensional form).

The Messina suspension bridge (3300 m of main span) is taken as a test case, since for very long span bridges the aeroelastic effects are dominant in the design. Due to the peculiar role played by the aeroelastic coupling of the wind-structure problem in the proposed methodology, even if the analysis procedure is suitable to evaluate the uncertainty effects on fluid–structure interaction of different bridges, the results that will be presented cannot be extended to all suspended bridges because they depend on aerodynamic characteristics and structural properties of the considered structure.

The paper is organized as follows. Section 2 introduces the analysis background: the fluid–structure interaction model; the algorithm used to assess the aeroelastic stability; the Monte-Carlo method; the uncertainties considered in the analysis.

In Section 3 numerical results are presented following these strategies:

- initially, a deterministic approach is used to perform a preliminary investigation to select the most relevant structural and aerodynamic parameters, on the total damping and critical wind speed estimation, by varying each parameter individually.
- Then Monte-Carlo Simulations (MCS) with Hypercube Latin Sampling are run to perform a multivariate analysis considering a simultaneous variation of all the most relevant parameters, previously selected through the deterministic analysis. This procedure allows to have a statistical distribution of the results, as suggested in other works (Matsumoto et al., 1996; Cheng and Li, 2009).
- Specific considerations about the considered test-case are reported.

Finally, conclusions are discussed in Section 4.

2. Analysis background

2.1. Self-excited wind loads

The aeroelastic stability analysis is performed using an iterative multi-modal eigenvalue approach in laminar flow on a complete scheme of the bridge. The aerodynamic forces are modeled using a sectional approach considering their interaction with deck, towers and cable system. To define the aerodynamic forces each bridge