Summary

Long span suspension bridges are prone to aeroelastic instability phenomena. Since the famous collapse of the Tacoma Narrows Bridge in 1940, flutter has been considered the most dangerous and catastrophic event. From then on, flutter analysis is one of the main concerns in suspension bridge design. Technological evolution of deck profile, as well as the significant increase in span length, raised new aspects and critical issues that were ignored in the old bridges design. For example, it is now known that the so-called super-long span bridges experience aerostatic-induced large deflections which may affect the aeroelastic stability threshold. Although these deflections were of minor significance on relatively short bridges, they were shown to have a major impact on bridges whose span approaches two kilometers. The Akashi Kaikyo Bridge, with a main span of 1991 meters, and the Çanakkale Bridge, whit a main span of 2023 meters (the actual word span record), are examples of such development. Moreover, in modern bridges, different types of flutter instabilities can be detected according to the involvement of different degrees of freedom or different aeroelastic forces. Each of them may be associated with a different physics, and countermeasures developed against one type of instability may not be adequate in countering a different type. For example, the streamlined aerodynamic section shapes, give the structure an exceptional level of stability against one-degree-of-freedom flutter while favoring the appearance of the two-degree-of-freedom flutter (classic airfoil flutter), where two or more structural vibrating modes are involved.

This work presents an effective and original approach to perform an enhanced linear dynamic analysis of suspension bridges subjected to the aeroelastic wind load. The equations governing the suspension bridge vertical and torsional motion provided by the linearized deflection theory are adopted to describe the bridge dynamics. Additional coupling terms are embedded in the equilibrium equations to include some aerostatic-induced nonlinearities. For this purpose, the linearization of the equilibrium equations is made around the prestressed bridge configuration under the dead load and the mean steady drag and lift forces. The non-stationary component of the wind load, defined via Scanlan's flutter derivatives, is embedded as a self-excited perturbation of the prestressed system.

A coupled multi-degree-of-freedom system is obtained by the Galerkin method and, for increasing values of wind speed, the damped linear dynamics, modulated by both the steady and the self-excited aerodynamic forces, is studied in the complex field. The interpretation of the complex eigen-solution provides a direct understanding of the modal interaction in the initiation of the instability, with special reference to the modal shape variation. Some peculiar aspects of the modal interaction, such as the curve veering of eigenvalue loci and the phase shift between different degrees of freedom characterizing the same modal branch, are highlighted.

A MATLAB script was developed to implement the procedure described above, which, iterating in a selected range of wind velocity and structural frequency allows for: (i) determining the variation of the bridge mode shapes and frequencies for increasing values of wind speed, including an effective description of the coupling between the two displacement components as well as the interaction between different vibration modes; (ii) detecting both single-degree-of-freedom (i.e. damping-driven) and coupled (i.e. stiffness-driven) flutter instability; (iii) detecting static divergence instability; and (iv) investigating geometric nonlinearities associated with the aerostatic load. The validation made with respect to both literature and in-house finite element analysis results, proved the model to be robust, effective and reliable. It represents a useful tool for preliminary aeroelastic stability analyses, validation of other numerical and experimental results, and for parametric investigations. In fact, the time required for setting-up the input parameters (bridge and aerodynamic data) and the computational time are much lower than those usually required by finite element analyses: approximatively ten times lower.

A consistent part of the work is dedicated to the use and the proposal of improvement of existing simplified analytic expressions of flutter derivatives describing the aeroelastic wind load. Computational Fluid Dynamic (CFD) analyses of double-deck and multi-box girders were performed

to determine the steady state aerodynamic coefficients, which were included in flutter derivatives analytic expression. A general expression of flutter derivatives of multi-box systems was derived from the enhancement of a superposition theory recently introduced in literature. Finally, the proposed methods have been successfully applied in several case studies, for which finite element models were also created to provide a direct comparison of the results obtained.
The limited percentage difference between the numerical and the analytical results provided a satisfactory validation (with the due limitations) of the analytic approach, which involves a significantly reduced calculation time. The analysis of the record-breaking bridges built over a century, from the George Washington Bridge of 1931 to the Çanakkale Bridge of 2022, outlines some of the main trends arising from the technological evolution and allows cautious prediction of the challenges that might affect the design of future bridges.
The Dissertation is structured into 3 parts.
Part I lays the theoretical groundwork upon which the analysis models, developed and utilized in the subsequent parts, are built. Chapter 1 offers an overview of the key advancements leading to the establishment of suspension bridge aeroelasticity, alongside recent developments in the field. Chapter 2 delves into the dynamic instability of linear mechanical systems, exploring benchmark examples and elementary schemes to provide a comprehensive understanding of various instability forms. Chapter 3 explores the theme of aeroelastic instability in suspension bridges, building upon the general features introduced in the preceding chapter. It provides wind load definitions and analytic foundations of the aeroelastic problem, addressing instability phenomena from an eigenvalue perspective, with a focus on the role of aerodynamic stiffness and damping in degrees of freedom interaction. Elementary schemes are presented for an in-depth understanding of the aeroelastic instabilities phenomenological aspects. In Chapters 2 and 3, a personal contribution is given in the originality of the synthesis and representation of the classical theories with focus on the information arising from the interpretation of the complex eigenvectors in the paradigmatic examples. In Chapter 4, the theoretical background of suspension bridge structural modeling is reported, outlining the main hypotheses underlying the analytic and finite element models employed in the Thesis.
Part II contains the innovative research insights of the Dissertation. Chapter 5 introduces the analytic model for multi-order linear flutter analysis, describing the equilibrium configuration prestressed by aerostatic lift and drag, the multi-order analytic framework derived from Galerkin discretization, and the iterative procedure for the stability analysis. Some features of the 16-DOF model implemented in the MATLAB framework are discussed with focus on the physical interpretation of the complex eigensolution. Chapter 6 explores applications of the analytic model, including model validation, discussion on the influence of aerostatic nonlinearities, and a parametric study examining the influence of flutter derivatives on stiffness-driven and damping-driven flutter instabilities. Chapter 7 addresses the problem of calculating flutter derivatives by analytic expressions involving the deck steady state aerodynamic coefficients. The generalities of the CFD models for the calculation of the deck pressure coefficients are illustrated and the results obtained are reported. Simplified approaches for double deck and multi-box systems are introduced and tested for the different case studies.
In Part III, the outcomes of the flutter analysis of the 14 bridges analyzed in the Thesis are collected. A systematic comparison of the results provided by the 16-DOF MATLAB code with those obtained by a full-order approach in the ANSYS APDL finite element package is provided. In Chapter 8, the suspension bridges built before the “airfoil revolution” brought by the Severn Bridge in 1966 are analyzed, whereas Chapter 9 examines modern long-span suspension bridges, with the final section dedicated to the planned bridge over the Messina Strait.