1.
Introduction

1.1. Inspiration

The inspiration to write this thesis derives from the pioneering article “Bridge engineering and aerodynamics” written by Ostenfeld & Larsen [53] in which the idea of using wings (or winglets) as a means to improve the aerodynamic behavior of large span bridges has been proposed.

The system is based on the idea of continuously monitoring oscillations caused mainly by wind forces on slender bridges and using control surfaces to generate aerodynamic forces to counterbalance any tendency to instability. Two concepts are shown in Figure 1-1. The potential increase of the wind critical velocity is obtained by controlling the rotation of winglets fixed to the bridge deck.

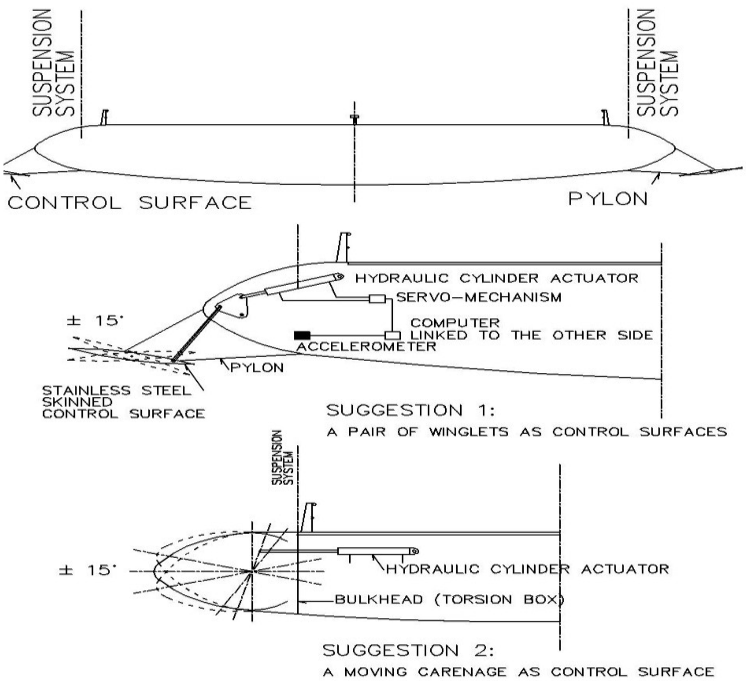

Figure 1-1 – Suggestions for implementation of Active Surface Systems in streamlined bridge girders, reproduced from Ostenfeld and Larsen.

The bridge deck and the control surfaces have aerodynamic profiles to minimize drag forces and along-wind displacements, leading to an overall low wind resistance, as Leonhardt [39] suggested as early as 1968. The chord width of the winglets, acting as control surfaces, corresponds to one tenth of the bridge width.

The winglets are located under the deck and their rotations are controlled to move in opposite directions to each other. It is necessary that the control surfaces are installed as far as possible from the deck, out of the local pattern of the wind flow around the streamlined box. The influence of vortex shedding in the wake of the windward surface over the leeward surface would have to be verified experimentally.

The principle is attractive because the aerodynamic forces increase in proportion to the square of the wind velocity and are therefore proportional to the forces acting over the bridge deck itself.

The location of the control surfaces is preferable under the bridge deck, where a laminar flow prevails, rather than above the deck, where railings, traffic barriers and several obstacles exist.

Standardized control surfaces fabricated with stainless steel cases encapsulating polyurethane foam (forming a kind of sandwich construction) are connected to the deck by 5 to 10 m distant aerodynamic pillars. Control rods located inside the pillars and activated by hydraulic cylinders with short rise time govern the rotation of the control surfaces. The hydraulic cylinders are activated by means of computer controlled servo-pumps. The computer operates on the basis of signals from accelerometers located in the deck box.

The reliability of the system would be accomplished by parallel independent systems connected to independent sources of energy as well.

The control surfaces always operate in opposite directions, with retarded phases to the pitching of the bridge deck, as shown later in Chapters 6 and 7. They are more efficient to oppose deck pitching than heaving, due to the restoring moments provided by the uplift forces on the wings and their distance to the center of symmetry of the structure.

Active control systems are envisaged in the future as basic elements in wind sensitive bridges to enhance the comfort of the users and reduce fatigue damage.

Several articles in the literature deal with the aerodynamic control of bridge deck flutter by control surfaces of the type shown in Figure 1-1, suggestion 1, as for example Wilde [95], Wilde & Fujino [96], [97], [98], Wilde, Fujino & Omenzetter [100], [101] and Preidikman & Mook [55]. Articles [96] and [101] were consulted extensively throughout the present thesis.

1.2. Additional contributions

An article written by Kobayashi & Nagaoka [31] in 1992, when the First International Symposium on Aerodynamics of Large Bridges took place in Copenhagen, deals with the problem of flutter suppression of a bridge deck by an active control method using control wings. Two dimensional theoretical analyses showed that the flutter velocity of the bridge deck could be increased up to infinite high figures. From the model tests, the flutter velocity was increased by a factor of two.

Figure 1-2 - Section model of bridge deck and alongside wings in the small wind tunnel of the Technical University of Hamburg-Harburg

Another important contribution is provided by Cobo del Arco & Aparicio [10], where the influence of aerodynamic appendages on the wind stability of box girders suspension bridges is examined, with special reference to the stability of bridges with very long spans (2000 to 5000m). The authors state that concerning stationary aerodynamic appendages, the most promising solution is to locate a winglet only in the leeward position.

TMDs for flutter control were more recently studied by Chen et al. [5], [6], [7], [8]. The investigations showed some improvements regarding flutter control but with the disadvantage of increasing the dead load.

Starossek & Aslan [79] present a novel aero elastic damper for flutter suppression of long bridges consisting of a small tuned mass damper (TMD), control surfaces and a transmission part which couples the movement of the TMD with the control surfaces. The middle plane of the wings and the bridge deck are positioned in the same horizontal plane. The mechanism can be seen in Figure 1-2. Korlin & Starossek [32] describe an active mass damper implemented to a bridge section model in a wind tunnel to enhance flutter stability. Servo motors controlling the rotational motion of control masses serve as actuators. The torque generated by rotational acceleration is used to control the angular motion of the section model.

Nissen et al. [48] describe the addition of actively controlled aerodynamic appendages (flaps) attached along the length of the bridge deck to dampen wind-induced oscillations in long suspension bridges. The model was validated through comparison with finite element calculations and wind tunnel experimental data on the Great Belt East Bridge in Danmark. The analysis showed that the critical wind speed for flutter instability and divergence is increased substantially by active control.

Passive control of the wings is also an alternative for flutter suppression, see for example Kwon, Soon-Duck et al. [34], Wilde [94], Wilde et al. [97], [100], and Omenzetter et al. [51], [52].

In two intriguing articles, Shubow [71], [72], provides a brief exposition of the results obtained in several selected papers on the following topics: Bending-torsion vibrations of coupled beams, flutter in transmission lines, flutter in rotating blades, flutter in hard-disk drives, flutter in suspension bridges and flutter of blood vessel walls.

A multidisciplinary approach to aero elastic studies of long bridges is studied by Hernandez [19]. A study of aeroelastic stability using CFD (computer fluid dynamics) is presented by Staerdahl et al. [74].

The effect of coupled flutter and modal damping is studied by Pfeil & Batista [54] and Jain et al. [21], [22], [23].

Bridge flutter prediction through use of finite elements is discussed by Starossek [76], [77].

1.3. Objective

The objective of this thesis is basically to check the hypothesis outlined in the previous section, i.e., if increase of wind critical speed of streamlined bridge decks with control surfaces is theoretically possible, how this can be done, and how the bridge behaves with time, as the two control surfaces respond to oscillations due to wind forces. The main questions are: How to establish the control laws; shall the control laws be enforced over the pitching or over the heaving mode of the bridge deck; can control surfaces be really effective in stabilizing the bridge againt flutter; how does the relative pitching of the two control surfaces affect the behavior of the deck, and how to obtain an optimal performance with regard to the critical wind speed.

1.4. Sequence of presentation

Chapter 2 is devoted to a review of recent past work on the aerodynamics and aero elasticity of bridge decks relevant to the present work. Chapter 3 is devoted to the formulation of rational function approximations (RFA) for unsteady aerodynamics. Several examples are presented therein. Chapter 4 deals with applications of the theory outlined in Chapters 2 and 3 to determine the critical velocity of single bridge decks. Deduction of the equations of motion of active aerodynamic control of bridge decks with two control surfaces is carried out in Chapter 5. Chapter 6 is dedicated to the determination of the standard optimal control of deck-wing systems as described in Chapter 5. Chapter 7 is dedicated to the improvement in control effectiveness of deck-wing systems by the application of a variable-gain concept. Chapter 8 is dedicated to the study of Gibraltar Bridge, with and without wings. The MATLAB programs used to study the Gibraltar Bridge are included in Chapter 9. These programs may prove helpful to future researchers when confronted with problems like the type of profile to consider in a certain environment, as well as in parametric studies. Chapter 10 presents a summary of the work done and suggests propositions for future work. Appendix A contains a brief report on geometric and dynamic similitude laws applied to bridge section models. Appendix B presents a short translation of the Brazilian Norm NBR 6122 - Wind forces on buildings [102]. Plots of the Theodorsen function and aerodynamic data concerning eight profiles of typical bridge decks can be found respectively in the Appendices C and D.