Aeroelastic Control of Long Span Suspension Bridges during Erection

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Summary

The 3D structural and aerodynamic modelling of a long span suspension bridge is considered and emphasis is placed on the simulation of the aeroelastic properties during the deck erection process. We then employ a leading-and trailing edge flap configuration on a finite deck length around the mid-point of the main span and investigate its effectiveness in raising the critical flutter and divergence speed. In order to account for modelling errors and uncertainties in the controller design process we invoke elements from robust control theory and a nonlinear optimization algorithm is proposed to achieve the performance objectives.

Keywords: Long-span bridges, thin aerofoil theory, flutter, controllable winglets, robust control, erection process, model reduction, constrained optimization, Humber Bridge

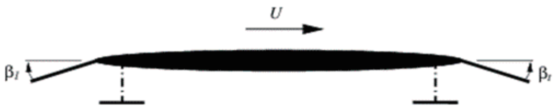
1. Introduction

Recent development in structural materials and construction technology has contributed to the increase in span length, flexibility and slenderness ratio of bridge design trends. It is widely appreciated that long-span bridges are prone to aerodynamic instabilities with the now iconic Tacoma Narrows bridge disaster (1940) serving as a reminder of the importance of efficient aerodynamic design. The increasing use of flat box girders to the alternative massy truss deck solution justifies the use of traditionally inappropriate classic thin airfoil theory for flutter analysis [1], as was formulated in Theodorsen's original work [2]. This theory also exposes a non-oscillatory instability known as torsional divergence, caused by loss of torsional rigidity.

The main thrust of this paper is to build on previous work [3] by extending into a full bridge aeroelastic model the analysis described therein with respect to suppression of aerodynamic instabilities making use of control theoretic means. The motivation for this is that a complete structural model is necessary for evaluating the bridge's multimodal behaviour and for uncovering the modal interplay which drives the structure in flutter instability. Another reason is that a full bridge model enables investigating different flap configurations and accounting for limited flap length along the deck. As opposed to following a frequency based approach for modelling the unsteady forces a high fidelity quartic rational function approximation (RFA) of the Theodorsen function is implemented [3] and the aerodynamic loading is cast FE framework, which allows the equations of motion to be expressed through a generalized eigenvalue problem approach.

The structural part of this work is based on Abdel Ghaffar's FE formulation [4] tailored for suspension bridges. The methodology described therein was altered to account for the closed box girder deck as well for modelling the bridge construction phase. Flutter aeroelastic instability during the early erection stages of the deck, Fig. 1, are more dangerous because the fundamental torsional mode is closer to the fundamental vertical mode and hence they couple at lower wind speeds. The low flutter speed limit observed during the early stages of erection justifies the use of controlled surfaces of the type shown in Fig.1 as a mean for making the bridge more aerodynamically stable.

The control strategy followed in this paper aims at stabilizing the system while achieving maximum stability margins or in other words better robustness to uncertainty. In setting up the optimization problem we make use of a model reduction procedure in order to bring the system in a manageable size for the task at hand



(a) (b)

Fig. 1: (a) *Cross section of a streamlined long-span suspension bridge with flutter suppression winglets.* (b) *Humber Bridge during erection.*

2. Methodology

The lift and moment on a system with a leading and trailing edge flaps is based on a transformation of the wing-flap-tab formulation, Fig. 2. The extra states due to flap dynamics are implemented in the FE model resulting in a closed loop system of the form given in the right-hand side of Fig. 2. The uncontrolled system is described by the plant $P(s)$ containing the structural dynamics and the non-circulatory part of the fluid mechanics. The controllers for the leading – and trailing edge flaps are $K_l(s)$ and $K_t(s)$. Both controllers receive the pitch angle of the corresponding element as input.

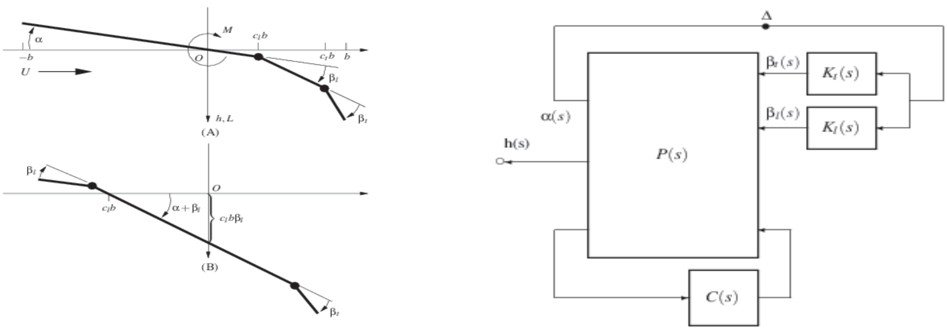


Fig. 2: Left-hand diagram presents the transformation of the Theodorsen-Garrick wing-aileron-tab configuration into a controlled bridge deck. Right-hand block diagram is the aeroelastic control system.

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