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CFD-based aeroelastic characterization of streamlined bridge deck cross-sections subject to shape modifications using surrogate models

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ABSTRACT

The classical approach currently used in the bridge engineering industry for the structural and aeroelastic design of bridges is based on an iterative heuristic process which includes wind tunnel testing. The dependency on experimental techniques for the aeroelastic characterization of the bridge deck cross-section requires a substantial amount of resources, and consequently the number of potential candidate designs must be limited.

The fast improvements in Computational Fluid Dynamics (CFD) techniques in recent years have led to its use in the industrial field, and consequently bridge design methods must be updated. This paper proposes a fully numerical strategy to overcome the classical iterative process in bridge deck shape design. Firstly, it consists in constructing a surrogate model of the aerodynamic response of the baseline cross-section and the allowed shape variations by conducting a set of CFD simulations of several sample designs. Then, the force coefficients and their slopes can be obtained for every design included in the design domain, the flutter derivatives can be approximated by the quasi-steady formulation, and the flutter velocity can be computed. This procedure is applied to two cable-stayed bridges with different spans, and the reported results are validated with wind tunnel tests.

1. Introduction

The main feature affected by the technological advances of the last century in the bridge engineering field is the increasing length of the main span of long-span bridges. The construction of the Great Belt Bridge, in Denmark, or the Akashi Kaikyo Bridge, in Japan, both opened in 1998, are good testimonies of these advances. In fact, between the late 1990's and the beginning of the 21st century several projects or very-long-span bridges were studied. This is the case of the Messina Bridge project (Diana (1993) and Miyata et al. (2003)), in Italy, the bridge across the Strait of Gibraltar that would link Spain with Morocco (Ostenfeld et al. (1995)), or any of the bridge projects over the Japanese straits reported by Ito (1998), including the Tsugaru Straits crossing with two main spans of 3–4 km long. Moreover, the recent construction of the Xihoumen Bridge, in China, or the Osman Gazi Bridge, in Turkey, confirms that the design of suspension bridges with spans between 1.5 and 2 km is being tackled more frequently in recent years. Furthermore, some recent research works have explored the viability of even longer super-long-span bridges (Ge (2016)). However, as these large and flexible structures were designed and built, new technical challenges related to wind induced loads or aeroelastic phenomena appeared, such as flutter instability, buffeting effects, or rain-wind-induced cable vibrations, as described by Miyata (2003).

Among the aeroelastic phenomena, flutter instability can be considered as one of the most important wind-induced effects in bridge design, given that it can cause the collapse of the whole structure (Simiu and Scanlan, 1996). This structural instability is principally driven by three crucial aspects. The first one consists of the bridge deck aerodynamics. In fact, the flutter response of the bridge can be strongly affected by the deck shape, as it has been shown for the Messina Strait Crossing Bridge project by Diana (1993) and Diana et al. (2013). The second one is related to the bridge stiffness, which has a determinant influence on the critical flutter velocity of a bridge, as studied by Astiz (1998) for the Gibraltar Bridge project. The last one is the structural damping, whose role in the aeroelastic behavior of bridges has been investigated, for example, by Ostenfeld and Larsen (1992).

Both the bridge aerodynamics and the bridge stiffness are controlled (or affected in the second case) by the bridge deck cross-section geometry. Therefore, its design is a top priority in long-span bridge projects. However, the aeroelastic characterization of deck cross-sections can be considered as one of the most challenging steps in the design of long-span bridges. It has been historically conducted by means of wind tunnel tests

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(see, for instance, Hjorth-Hansen (1992), Larose et al. (1992) and Diana et al. (2004)). However, the improvements in Computational Fluid Dynamics (CFD) in the last decades (reviewed in Cochran and Derickson (2011), Blocken (2014) and Tamura and Van Phuc (2015)), make this methodology a suitable and increasingly reliable alternative to ascertain the aerodynamic behavior of bridge deck cross-sections, as it has been proved by Sarwar et al. (2008), Mannini et al. (2010) and Šarkić et al. (2012), among others. In fact, some research works have explored the use of these CFD techniques to obtain numerically the flutter response of a bridge design, as reported by Ge and Xiang (2008).

The present work focuses on the aeroelastic characterization of a generic streamlined deck cross-section and its shape variations by means of numerical techniques to allow studying their qualitative and quantitative effect on bridge deck aerodynamics. This requires identifying the aeroelastic parameters responsible for the bridge flutter response using a computer based approach. In this work a multidisciplinary approach is proposed, where CFD simulations, surrogate modeling, quasi-steady aeroelastic formulation and multi-mode flutter analyses, are linked together. This allows to obtain numerically the flutter velocity response surface of a bridge in the considered design domain, which is a useful tool for the aeroelastic design of long-span bridges. This numerical process must be at the same time accurate and efficient in terms of the expected computational burden. A remarkable characteristic of this work is the emphasis put in the validation of the proposed methodology, aiming to provide a clear picture of the strong points and the limitations of the novel design procedure proposed herein.

Other researchers have studied the effects of shape variations in the aerodynamics of bridge decks, mainly by means of experimental methods. This is the case of the work by Nagao et al. (1993), where a detailed experimental study was carried out analyzing the aerodynamics of two cross-sections subject to several shape modifications. In addition, the effects of several edge fairing geometries on the aerodynamic response were analyzed in the aforementioned reference, as well as in another work by de Miranda and Bartoli (2001). More recently, Larsen and Wall (2012) studied the changes in the Strouhal number and vortex-induced vibration response produced by variations of the lower corner angle of a monobox cross-section by means of wind tunnel tests.

Fully computational approaches for the shape design problem of decks, as the one proposed herein, can provide an efficient alternative to heuristic procedures based on wind tunnel testing since in this way, well known methods such as sensitivity analyses, parameter variation studies and optimal design can be applied. This work aims to be a first step towards the practical application of combined aeroelastic and structural optimization of bridges, as outlined by Hernández et al. (2016) and Cid Montoya et al. (2016).

In the following sections, a fully computational strategy is developed for the aeroelastic characterization of a bridge when shape variations of the deck geometry are considered. All the numerical processes involved in the strategy are formulated and outlined. The strategy is applied to the well known G1 Scanlan's section (Scanlan and Tomko (1971)), considering variations on its width and depth. The numerically computed force coefficients and flutter derivatives provided in this work are validated with experimental results obtained from a wind tunnel campaign comprising three sectional models chosen among the candidate designs inside the considered design domain. Later, the flutter velocity of the bridge is assessed using the proposed methodology and it is compared with the flutter response obtained using the experimental flutter derivatives in order to validate the whole process.

2. Description of the fully computational strategy to aeroelastic characterization of the bridge considering deck shape variations

The classical approach used in heuristic bridge design, which is described for instance in Chen and Duan (1999) can be simplified to three stages: a first one in which the static design of the bridge is carried out, a second stage where the air-flow force coefficients are obtained and the structure subject to these loads is analyzed, and a final stage in which the dynamic stability of the structure is assessed, including gust responses, flutter instability and vortex-induced oscillations. The interdependence among these three phases is that the subsequent analyses depend on the shape of the cross section established in the first step. If any of the design requirements considered in any of the last two steps is not achieved, the design must be modified, and the first step is repeated, giving place to an iterative process that increases the cost of the design itself. This process has been defined in this way because aerodynamic and aeroelastic wind tunnel tests of the bridge are required and any change in shape requires a new round of wind tunnel testing. However, assuming the capabilities of the CFD techniques and using the numerical strategy that will be outlined next, the static and dynamic wind-induced effects can be evaluated simultaneously for any considered design, which simplifies the process and lowers the associated design costs.

The piece of research reported in this paper describes and applies a CFD-based strategy for obtaining the aeroelastic response of any candidate geometry included inside a design domain, that has been defined beforehand. This methodology is based on the use of CFD techniques to create a surrogate model that provides the force coefficients and their slopes for deck geometries within the pre-defined design domain that may be analyzed during the bridge design process. From this surrogate model, and using the quasi-steady formulation, the flutter derivatives of any candidate streamlined deck shape can be approximated. This allows to obtain the flutter derivatives of any shape design considered in the design domain recursively, as required along the iterative design process of the bridge. A sketch of the process for obtaining the flutter derivatives is depicted in Fig. 1, and can be summarized in the steps outlined next.

The first step consists of the identification of the design variables and the definition of the design domain of the bridge deck shape. This requires the identification of the shape design variables that control the modifications of the bridge deck geometry and the definition of the

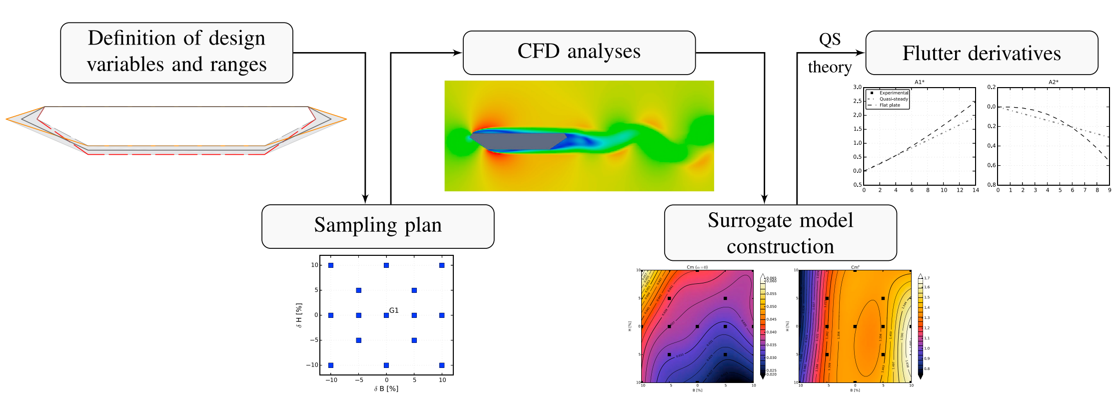

Fig. 1. Flowchart of the process for obtaining numerically the flutter derivatives for any design included inside the design domain.