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Indicial functions and flutter derivatives: A generalized approach to the motion-related wind loads

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ABSTRACT

This paper presents a general time-domain description of the loads acting on a moving cylindrical body immersed in a two-dimensional low-speed flow, aiming to consistently extend the framework of thin airfoil theory to mildly bluff sections, such as those usually employed for decks of modern long-span bridges. In order to systematically accommodate typical features of bluff-body aerodynamics, the classical Theodorsen and Wagner results are reorganized within a unified dimensionless approach, and generalized preserving their main formal structure. Accordingly, circulatory and non-circulatory contributions are separately described and superimposed, and generalized downwash-related terms are introduced. The strong duality between time-domain and frequency-domain representations is focused, and direct relationships between proper Wagner-like indicial functions and Theodorsen-like circulatory functions are deduced. Thereby, following the Scanlan formulation for bridge deck sections, flutter derivatives are represented by superimposing circulatory and non-circulatory effects, resulting in a frequency-domain description fully consistent with the Theodorsen's theory.

The model is based on few parameters that can be estimated by simplified strategies and, when applicable, by asymptotic relationships. An identification procedure involving few experiments or numerical simulations is proposed and numerically implemented. Simulation results obtained in the case of a flat thin plate and of a closed box section, similar to the cross-section of the Great Belt East Bridge, are successfully compared with theoretical and/or numerical solutions, highlighting effectiveness and soundness of the presented identification strategy.

1. Introduction

The problem of evaluating the forces acting on a moving cylindrical body immersed in a low-speed flow is of great importance in many industrial and structural applications, ranging from aeronautics to mechanical and civil engineering. The case of the airfoil moving within an inviscid two-dimensional flow was solved by Wagner (1925) and Theodorsen (1935) under the assumption of a zero-thick profile (namely, the thin airfoil) approached by the flow with a small angle of incidence. The time-domain formulation based on the Wagner indicial approach, and the mixed frequency-time description developed by Theodorsen were reorganized and further developed by many authors (Bisplinghoff et al., 1996; Fung, 1993; Scanlan et al., 1974; Scanlan, 1996; Peters, 2008), revealing

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the main theoretical background needed to systematically explain some complex fluid–structure interaction phenomena, such as the flutter instability.

Nevertheless, when unstreamlined bodies are considered, possible large flow separation, reattachment, recirculation zones and vortex shedding can occur, inducing significant unsteady effects and preventing to identify a thin and well defined boundary layer. Thereby, in these cases the hypothesis of inviscid and fully attached flow, generally acceptable for streamlined bodies immersed in a flow with a small angle of attack, must be often rejected. Accordingly, the description of the motion-induced loads on cylindrical bodies with a bluff sectional geometry, such as typical bridge decks, cannot be directly obtained by using the thin airfoil theory.

In order to overcome such a drawback several theoretical and computational approaches have been developed, based on both frequency-domain and time-domain descriptions. In the context of bridge aerodynamics, motion-induced forces are synthetically described by distinguishing in-phase and out-of-phase components with respect to the time evolution of the motion, instead of the distinction between circulatory and non-circulatory effects as for the thin airfoil (Cararcoglia and Jones, 2003). As a matter of fact, if proper circulatory and non-circulatory terms appear as clearly recognizable in the thin airfoil theory, in the case of bluff sections a certain distinction can be made only referring to flow memory-dependent (pseudo circulatory) and independent (pseudo non-circulatory) contributions.

As regards frequency-domain approaches, Scanlan (Scanlan and Tomko, 1971; Scanlan, 1993; Scanlan and Simiu, 1996; Scanlan, 1996; Scanlan and Jones, 1999; Scanlan, 2001) profitably exported some features of the Theodorsen results, describing the wind loads induced by sectional harmonic motions by means of a linearized format based on experimentally evaluated frequency-dependent filter functions (namely, the flutter derivatives), that supplied the lack of closed-form analytical formulations.

Time-domain approaches, generally established by introducing more than one indicial function, did not develop as much as the frequency-based models, due to the difficulties arising in the direct experimental evaluation of the response to step-wise motions. In the context of the bridge aerodynamics and following the classical results for the airfoil by Garrick (1938) and Jones (1940), Scanlan and coworkers (Scanlan et al., 1974; Scanlan, 2000) were the first to combine Fourier synthesis and rational approximation techniques for analytically extracting the indicial functions from the experimentally derived flutter derivatives. Starting from more refined formulations of the indicial response and considering generalized rational approximation procedures, similar approaches were recently developed in Cararcoglia and Jones (2003), Costa and Borri (2006) and Costa (2007). Nevertheless, indicial responses indirectly estimated from the flutter derivatives include implicitly non-circulatory contributions associated with the experimental procedures employed to determine flutter derivatives themselves. Therefore, when memory-independent effects are not negligible, the corresponding estimates of the indicial functions cannot be generally considered as fully consistent with the Wagner theory, that formally describes circulatory effects only.

As a matter of fact, the relative importance of non-circulatory contributions with respect to circulatory ones can be considered as problem dependent. For example, pseudo non-circulatory effects can be generally considered a priori of secondary importance for a truss deck with large openings and grillages, or when the flow regime and the sectional geometry induces wide bluff features characterized by large vortex structures. Nevertheless, many modern long-span bridges exhibit almost elongated and streamlined cross-sections characterized by mildly bluff performances. As a consequence, this occurrence on one hand does not allow to apply directly the ideal thin airfoil model but, on the other hand, can lead to non-circulatory effects generally not completely negligible with respect to the circulatory ones (Jones et al., 2003). This matter can be more evident when eccentricity between the elastic axis and the gravity axis, and/or small values of the reduced velocity (or equivalently high values of the reduced frequency) are considered.

In this context, a general theoretical framework based on the main formal structure of the classical results of Theodorsen and Wagner, and developed without introducing simplifications a priori, would contribute to overcome some consistency problems with respect to the thin airfoil model. In this way, the mutual role played by memory-independent terms and pseudo-circulatory downwash effects could be highlighted, opening also to the possibility of drawing some insights on issues to which the thin airfoil theory does not provide suitable indications (e.g., drag force components).

In order to directly identify indicial responses on bridge decks, allowing also the indirect extraction of flutter derivatives, very few successful experimental techniques can be found in the literature (Yoshimura and Nakamura, 1979; Caracoglia and Jones, 2003). This lack is mainly due to the drawbacks associated with the experimental replicability of an exact step function, as well as with the controllability of a suitable quasi-step description. As an alternative and/or support to the experimental methodologies, different computational approaches have been recently proposed, aiming to furnish direct estimates of aerodynamic indicial responses. Referring to two-dimensional grid-based methods, two different strategies are generally employed. The first considers a motionless solid region immersed in the fluid domain, simulating the step-response by suitable flow boundary conditions. The second directly simulates the motion of the solid domain within the flow, prescribing a smoothed-ramp motion of the section during a finite time in order to overcome the computational problems involved by the exact step-wise condition (Lesieutre et al., 1994; Bruno and Fransos, 2008). The first attempt to directly determine indicial functions by using computational fluid dynamics (CFD) was made by Brar et al. (1996) and was based on the first type of strategy; but, as highlighted in (Bruno and Fransos, 2008), some questionable aspects can be traced due to the adopted boundary conditions. Addressing aeronautical and industrial applications, more effective numerical formulations were recently developed, modeling step-wise body motions by the field velocity approach (Singh and Baeder, 1997; Sitaraman and Baeder, 2004; Yee et al., 2007). As regards the second class of numerical methods, mention is herein