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Numerical wind tunnel for aerodynamic and aeroelastic characterization of bridge deck sections

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ABSTRACT

The aim of the present study is to propose a reliable engineering procedure to analyze bridges subjected to wind loads by-passing the expensive wind tunnel tests thanks to numerical simulations. These exploit Kratos, a free multi-physic FEM code developed by the Kratos Team at CIMNE in Barcelona, and, specifically, an adaptation to the long-span bridge case of its numerical tool for simulation of in-wind ultra-lightweight structures developed within the uLites project (supported by the Research Executive Agency in the Seventh Framework Programme of the European Union, SP4-Capacities, Research for the benefit of SMEs, FP7-SME-2012 GA-314891, see http://www.cimne.com/websasp/ulites/). Time histories of the forces induced by the flow around the sections are used to calculate aerodynamic and aeroelastic parameters through statistical, frequencies extraction and fitting algorithms. Several analyses have been performed to derive rules for a reliable and stable evaluation of these aggregated parameters for engineering purposes. Results obtained for the sections of Great Belt Bridge (Denmark) and of the bridge on A31 highway over Adige river (Italy) are shown. Both static analyses (CFD procedure with fix boundaries) and imposed-displacements analyses (CFD with ALE) give results that are comparable with those coming from wind tunnel testing and from literature; evaluated parameters also manifest regular trends and values little influenced by CFD setting. These facts represent proofs of the reliability of the proposed procedure.

1. Introduction

In the last decades new materials and build techniques allowed the construction of taller and longer but lighter structures (such as suspended and cable-stayed bridges, chimneys and roofs) that easily suffer of aeroelastic phenomena. Engineering analysis of such structures requires specific approaches, different from those commonly used for standard structures, because of the peculiarity of the wind-induced loads that could depend on structural displacements and velocities. They involves aerodynamic (force coefficients c_D, c_L, c_M and Strouhal number St) and aeroelastic (flutter derivatives A_i and H_i) coefficients that are evaluated in general with wind tunnel simulations on scaled models or with numerical analyses (CFD).

2. Evaluation of aerodynamic and aeroelastic parameters

Considering the cross-section of an elongated body (such as a bridge deck or a tower) with three degrees of freedom (DOFs → horizontal translation p, vertical translation h and rotation α) and having defined a proper reference system (Fig. 1), forces on section induced by fluid with an incoming velocity V (drag D, lift L and moment M) can be expressed as:

$$D = D_{st} + D_b + D_{se} \quad (1)$$

$$L = L_{st} + L_b + L_{se} \quad (2)$$

$$M = M_{st} + M_b + M_{se} \quad (3)$$

In Eqs. (1)–(3) forces on section are defined as the sum of three contributions: the static one (*st* subscript), the one connected to buffeting (*b* subscript) and the one related to self-excited actions (*se* subscript).

Each one of the three contributions composing the wind-induced forces can be described thanks to specific *aerodynamic and aeroelastic parameters*. In common practice these are determined thanks to wind tunnel tests on scaled *section models*: a limited portion of bridge deck is modeled and mounted on actuators to make it rotate to fixed positions (varying angle of attack) and/or oscillate with prescribed sinusoidal motions on

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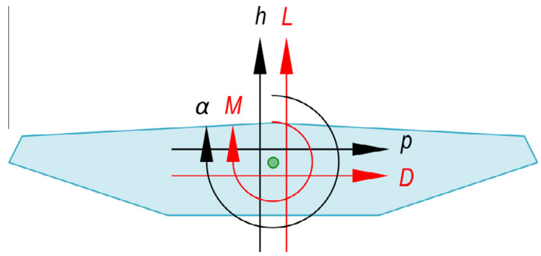

Fig. 1. Reference system for degrees of freedom and forces: α = rotation, h = vertical translation, p = horizontal translation, M, L, D = moment, lift and drag forces on section.

one of the DOFs [2]. Forces acting on the motionless or moving model are measured on prescribed inflow wind, recorded and post-processed with the procedures later introduced.

Static contributions (D_{st}, L_{st} and M_{st}) are described through aerodynamic coefficients c_D, c_L and c_M as in Eqs. (4)–(6), where ρ is fluid density, $\overline{V}$ is the average inflow velocity and l is a dimension defining the problem. In general section height H is used for c_D and section width B for c_L and c_M.

$$D_{st} = \frac{1}{2} c_D \rho \overline{V}^2 l \quad (4)$$

$$L_{st} = \frac{1}{2} c_L \rho \overline{V}^2 l \quad (5)$$

$$M_{st} = \frac{1}{2} c_M \rho \overline{V}^2 l^2 \quad (6)$$

Inflow velocity V is in general a non-constant parameter that can be considered as the sum ($V = \overline{V} + v'$) of a time-averaged constant quantity $\overline{V}$ and a fluctuating non-constant quantity v' due to the turbulence having null average value ($\bar{v}' = 0$). This stands for the main (horizontal) direction of the wind while in the orthogonal (vertical) direction velocity is a fluctuating non-constant quantity w' ($\bar{w}' = 0$).

Aerodynamic coefficients are evaluated through specific wind tunnel tests recording time histories of forces on the motionless section model with incoming wind having prescribed $\overline{V}$. Average values of D_{st}, L_{st} and M_{st} are then introduced on rearranged Eqs. (4)–(6) to obtain c_D, c_L and c_M. So D_{st}, L_{st} and M_{st} in the same equations have to be considered as average values of time histories.

Fourier analysis of lift time histories, moreover, allows the evaluation of the frequency of vortex shedding and so of the Strouhal number of the section ($St = fl/\overline{V}$).

Wind fluctuating components v' and w' cause an instant change of angle of attack that leads to buffeting forces (D_b, L_b and M_b) that are expressed in Eqs. (7)–(9) in which aerodynamic coefficients derivatives on angle of attack are expressed as c'_D, c'_L and c'_M.

$$D_b = (c'_D - c_L)\frac{w'}{\overline{V}} + 2c_D\frac{v'}{\overline{V}} \quad (7)$$

$$L_b = (c_D + c'_L)\frac{w'}{\overline{V}} + 2c_L\frac{v'}{\overline{V}} \quad (8)$$

$$L_b = c'_M\frac{w'}{\overline{V}} + 2c_M\frac{v'}{\overline{V}} \quad (9)$$

Self-excited forces are so defined because they depend on structural displacements: invested body moves due to wind forces, displacements modify pressure and velocity fields around it and this induces variation of wind actions and so forth recursively. This mutual influence could lead to motion instability with potentially destructive effects on the structure. Theodeorsen [20] found out an analytical formulation of L_{SE} and M_{SE} for the thin airfoil pointing out their dependence on displacements, velocities and accelerations through a complex function (*Theodorsen's circulatory function* $C(k)$) depending on motion frequency through the parameter k ($k = B\omega/2\overline{V}$, with ω the circular frequency). Unfortunately this solution stands only for thin bodies (airfoils, wings, etc.) and can't be applied on bluff bodies such as bridge cross-sections. Scanlan [15], in analogy with the solution of the thin airfoil, proposed to treat flutter on bluff bodies expressing the self-excited forces D_{SE}, L_{SE} and M_{SE} as combinations of displacements and velocities multiplied by coefficients called *flutter derivatives* (A_i, H_i, P_i, $i = 1,6$) depending on motion frequencies. Their expression is reported in Eqs. (10)–(12) with the same form and system of reference used by Lazzari et al. [12].

$$D_{SE} = \frac{1}{2}\rho\overline{V}^2 B\left(KP_1\frac{\dot{h}}{\overline{V}} + KP_2\frac{B\dot{\alpha}}{\overline{V}} + K^2P_3\alpha + K^2P_4\frac{h}{B} + KP_5\frac{\dot{p}}{\overline{V}} + K^2P_6\frac{p}{B}\right) \quad (10)$$

$$L_{SE} = \frac{1}{2}\rho\overline{V}^2 B\left(KH_1\frac{\dot{h}}{\overline{V}} + KH_2\frac{B\dot{\alpha}}{\overline{V}} + K^2H_3\alpha + K^2H_4\frac{h}{B} + KH_5\frac{\dot{p}}{\overline{V}} + K^2H_6\frac{p}{B}\right) \quad (11)$$

$$M_{SE} = \frac{1}{2}\rho\overline{V}^2 B^2\left(KA_1\frac{\dot{h}}{\overline{V}} + KA_2\frac{B\dot{\alpha}}{\overline{V}} + K^2A_3\alpha + K^2A_4\frac{h}{B} + KA_5\frac{\dot{p}}{\overline{V}} + K^2A_6\frac{p}{B}\right) \quad (12)$$

p, h, α, $\dot{p}$, $\dot{h}$, $\dot{\alpha}$ are horizontal translation, vertical translation and rotation and their first derivatives on time (velocities); K is the *reduced frequency* ($K = B\omega/\overline{V}$). Usually, in aeroelastic study of bridges (and in this paper) they are expressed on *reduced velocity* U_R ($U_R = \overline{V}/fB = 2\pi/K$, with $\omega = 2\pi f$) rather than on K.

Flutter derivatives are evaluated thanks to wind tunnel tests on section models executed with specific procedures. One of the most used is the *forced displacements method* that consists in simulations with fixed inflow velocity $\overline{V}$ with the invested body moving with a

Table 1
Forced displacements procedure – evaluated parameters and imposed motion.

Parameters	Forced horizontal translation	Forced vertical translation	Forced rotation
Motion	$p(t) = p_0\ sen(2\pi ft)$ $h(t) = 0$ $\alpha(t) = 0$	$p(t) = 0$ $h(t) = h_0\ sen(2\pi ft)$ $\alpha(t) = 0$	$p(t) = 0$ $h(t) = 0$ $\alpha(t) = \alpha_0\ sen(2\pi ft)$
Flutter derivatives	$P_5\ P_6$ $H_5\ H_6$ $A_5\ A_6$	$P_1\ P_4$ $H_1\ H_4$ $A_1\ A_4$	$P_2\ P_3$ $H_2\ H_3$ $A_2\ A_3$
U_R	$\frac{\overline{V}}{fB}$	$\frac{\overline{V}}{fB}$	$\frac{\overline{V}}{fB}$