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Aerodynamic instability of a bridge deck section model: Linear and nonlinear approach to force modeling

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A B S T R A C T

The aerodynamic behavior of a bridge deck section model with a simple single-box shape was characterized in wind tunnel. At large nose-up mean angles of attack, a torsional instability arises, outlining a situation in which nonlinear aeroelastic effects may be critical. Such condition represents an interesting case to develop and validate nonlinear models for the aeroelastic problem. The experimental campaign allowed both to characterize the aerodynamic forces using forced motion tests and to study the aeroelastic behavior of the section model, when excited by actively generated turbulent wind. These aeroelastic tests are used to validate a numerical time-domain model for aerodynamic forces that takes into account the nonlinearities due to the reduced velocity and to the amplitude of the instantaneous angle of incidence. Results are critically analyzed and compared with those obtained with a linear model.

1. Introduction

The combination of large deck motion components and large turbulent components in wind velocity can induce large fluctuations of the instantaneous angle of attack. This is a critical aspect in aeroelastic analysis since large variations of the angle of attack may lead the deck to work in conditions in which nonlinear effects of aerodynamic forces are important. In such situations, linearized approaches (e.g. Jain et al., 1996; Minh et al., 1999; Chen et al., 2000; Caracoglia and Jones, 2003) show their intrinsic limits, whereas fully nonlinear approaches are required to model the deck response and they may provide a more accurate estimation of the instability onset. Nonlinear analyses (e.g. Diana et al., 1995; Minh et al., 1999; Chen and Kareem, 2001, 2003; Zhang et al., 2002) mainly focused on the nonlinear dependence of flutter derivatives and aerodynamic admittance functions on frequency. Recently Diana et al. (2008b) developed a promising model, based on the aerodynamic hysteresis loop concept, which accounts for nonlinear effects due to both frequency and amplitude of the instantaneous angle of attack.

In the present paper the hysteresis loop approach is considered and similar experimental investigations are applied to study the nonlinear aeroelastic effects on a simplified deck section model. A wind tunnel experimental research was carried out on a deck section model (see Fig. 1) at the Department of Mechanical Engineering of Politecnico di Milano. Experimental tests allowed a detailed aerodynamic characterization of a simple single-box shape deck that shows interesting nonlinear effects that lead to instability at large nose-up mean angles of attack. The wind tunnel tests allowed to define all the static and dynamic aerodynamic coefficients that are required by linear and nonlinear numerical modeling of the problem by means of forced motion tests (Diana et al., 2004). Furthermore, the experimental campaign allowed to measure the aeroelastic response of the deck section model excited by actively generated turbulent wind conditions (Diana et al., 2004). During these free motion tests both forces and displacements of the elastically suspended model were contemporaneously recorded for different turbulent wind conditions. For this purpose the sectional model was equipped with a series of pressure taps to measure forces, while displacements were measured by an infrared measurement system during free motion tests and by laser transducers during forced motion tests.

A torsional instability at large nose-up mean angle of attack is present for a wide range of reduced velocities (negative value of the a_2^* coefficient at $\theta_m = 6^\circ$). Aeroelastic effects make the suspended sectional model prone to a 2-dofs instability, with an unusual torsional–lateral coupling. The control of the incoming turbulent wind allowed to investigate specific operating conditions where the deck is working close to instability and the small changes in the wind turbulence content may drive the deck behavior to cross the stability threshold.

These specific experimental tests, performed around a stable equilibrium configuration ($\theta_m \approx 3.5^\circ$), highlight that a large

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Nomenclature

y	horizontal deck motion, positive along horizontal wind
z	vertical deck motion, positive upward
θ	torsional motion, positive if nose-up
θ_m	mean angle of attack
V	average horizontal wind velocity component
v	deterministic turbulent horizontal wind velocity component
w	deterministic turbulent vertical wind velocity component
ρ	air density
B	deck chord length
L	sectional model length
ω	circular frequency of oscillation
V^*_ω	reduced velocity $V^*_\omega = V/(\omega B)$
V^*	reduced velocity $V^* = 2\pi V^*_\omega$
ψ	instantaneous angle of attack, defined in Eq. (4)
$\dot{\psi}$	time derivative of ψ
a^*_j	j-th torsional flutter derivative
χ_θ	torsional admittance function
C_D	drag force coefficient; force is positive if along wind
C_L	lift force coefficient; force is positive if upward
C_M	pitching moment coefficient; moment is positive if nose-up
β_j	coefficients of the model defined in Eq. (5)
i	imaginary unit

amplitude of the instantaneous angle of attack, may lead the deck to work between stable and unstable conditions, which result in a dangerous limit cycle. This instability mechanism shows important nonlinear effects and therefore it represents an interesting case to develop and validate nonlinear numerical models for the aeroelastic problem. Therefore, such operating condition is used to validate the nonlinear numerical model (Diana et al., 2008b), whose results are compared with both experimental data and linear model results (Diana et al., 2005), in terms of forces and displacements.

In Section 2 we summarize the main characteristics of the experimental setup. The aerodynamic behavior using a linear approach is critically discussed in Section 3. In Section 4 nonlinear effects on instability are analyzed and modeled. The proposed nonlinear model is validated and compared with a linear one in Section 5. Final remarks are reported in Section 6.

2. Experimental setup

Wind tunnel tests were performed at Politecnico di Milano. Tests were designed to achieve the following goals: complete definition of aerodynamic and aeroelastic forces including effects of aerodynamic nonlinearities to compare linear and nonlinear approaches; complete aeroelastic characterization of the suspended section model, in terms of input (turbulent wind) and output (forces and displacements) for numerical model validations.

2.1. Deck section shape

Following the previous considerations, we studied a single-box deck section with a simple shape. The deck shape is taken from an actual highway bridge, but without the barriers on the upper surface. This simplification allows the measure of the aerodynamic forces directly through the integration of the pressure distribution. The deck section model is 2.91 m long and the geometry and main dimensions of the section are reported in Fig. 1.

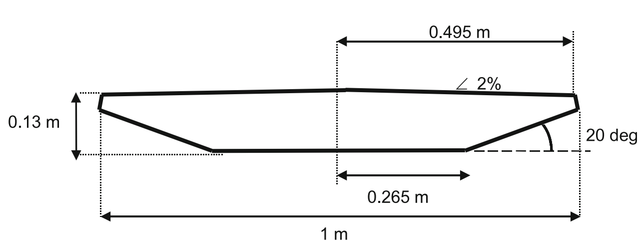

Fig. 1. Deck section dimensions and shape.

2.2. Forcing systems

Three computer-controlled hydraulic actuators drive the forced motion tests, generating a multi-degree of freedom harmonic motion around a user-defined average angle of attack. Two different kinds of motion law were used to measure flutter derivatives and aerodynamic hysteresis loops: torsional motion and vertical motion.

In free motion test configuration, the model is suspended in the wind tunnel test section by means of steel cables. A harmonic wind wave is generated by an active turbulence generator made by a horizontal array of 10 NACA 0012 profile airfoils, 4 m wide. The airfoils are driven by two brushless motors giving a pitching motion with a user-defined motion law in terms of frequency contents and amplitude. The turbulence generator is positioned 7 m upwind the model, while the incoming wind measure is performed one chord before the leading edge by means of a 4-holes probe that resolves the instantaneous vertical and horizontal wind components. The wind tunnel residual turbulence intensities in the vertical and horizontal directions are, respectively, I_w= 1.1% and I_u= 1.6%, with integral length scales $^x L_w$ = 0.025 m and $^x L_u$ = 0.124 m. These values are negligible with respect to the actively generated turbulent component. A partial picture of the experimental setup is given in Fig. 2.

2.3. Force measurements

A pressure measurement system was set up in order to prevent inertia forces subtraction problems during free motion tests (Diana et al., 2004). Pressure is measured on a ring of 78 pressure tabs around the middle section of the sectional model (see Fig. 3), at a sampling frequency of 100 Hz. Sixteen pressure taps are distributed along four lines aligned with the deck axis, two in the upper part and two in the lower part, to measure the pressure distribution correlation in the axial direction. The distribution of the pressure taps was studied to refine the measure where strong pressure gradient are expected (see Figs. 3 and 6). An example of pressure correlation along the deck axis is reported in Fig. 4.

2.4. Motion measurements

During forced motion tests, two laser transducers measure the deck vertical and torsional displacement when the model is linked to the oil dynamic actuators. During free motion tests, a system of three infrared cameras allows a nonintrusive measurement of the deck displacements. The model displacement is reconstructed by measuring the position of 10 markers located on the upper surface of the deck model. These markers reflect the infrared light that is emitted by