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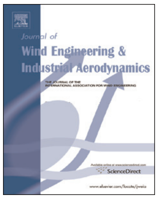

Transient flutter analysis of bluff bodies

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ABSTRACT

This paper deals with the flutter theory for bridge decks and presents a new approach for the determination of 27 time domain dynamic force coefficients using forced motion of the deck section at either constant absolute speed (triangular wave form) or constant absolute acceleration (parabolic wave form). These coefficients are then introduced in a transient nonlinear flutter analysis where the wind speed is varied in order to predict the stability curve of a 3 degrees of freedom deck sections. This allows for considering the nonlinear nature of the flutter phenomenon, i.e. its variation according to multiple quantities (wind speed, frequency of motion, amplitude of motion, angle of attack, etc.), when predicting flutter amplitude at any wind speed. Results show good agreement with predictions from complex eigenvalue analysis and the stabilization of flutter was observed at different levels of vibration according to the wind speed. The effect of the aerodynamic mass is also studied and its non-inclusion is shown to lead to possible non-conservative results.

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1. Introduction

Bridges are typically designed to withstand severe wind conditions and, in the case of long span bridges, their lightweight construction makes them prone to wind-induced oscillations. Well-known bridge failures have alerted engineers and characterizing the aerodynamic stability of these slender structures is now an important design consideration.

The equation of motion including the self-excited forces, as developed by Scanlan and Rosenbaum (1951), is based on flutter derivatives that are either aerodynamic rigidity or damping matrix terms; these terms are function of the reduced frequency, $b\omega/U$, where b is the half-deck width, ω is the circular frequency of motion and, U is the wind speed.

Flutter derivatives are typically extracted from free decay wind tunnel sectional test (Falco et al., 1992; Prud'homme et al., 2014b; Scanlan and Tomko, 1971; Singh, 1997). In this test, a reduced scale section of the bridge deck is mounted on a dynamic force balance in the wind tunnel. It is typically mounted on a 2 degrees of freedom (DOF) balance representing rotation and lift. For each wind speed, the model is simply pulled and release and the system parameters, including the derivatives, are identified from the decay signal. In addition, the onset of instabilities can also be measured in this test. The extraction of derivatives with free decay test presents a number of experimental limitations such as the difficulty to independently assess the effect of frequency and amplitude of movement, for while forced motion tests are required.

The forced motion approach is much more complex by nature: it requires a dynamic system to impose an harmonic motion to the model. The aerodynamic forces and the displacements are simultaneously recorded and are used for the direct calculation of the flutter derivatives. A few uses of this approach are found in the literature (Diana et al., 2004; Li, 1995; Matsumoto, 1996). It allows accurate control of the motion (frequency and amplitude) and can provide a steady amplitude compared to free decay motion. This represents an undeniable advantage for parametric studies, especially to isolate the effect of the amplitude on the self-excited forces.

Using either one of the latter approaches, a few studies reported that flutter derivatives are nonlinear functions of the amplitude of motion, its frequency and the mean angle of attack (Chen and Kareem, 2001; Falco et al., 1992; Li, 1995; Scanlan, 1997). Chen (2007) studied the effect of variation of flutter derivatives of a box section on the prediction of the flutter speed by multiplying each of the eight derivatives individually by either 0.5 or 2.0. The results show a variation of up to 33%. Since it is generally not possible to extract the derivatives at the same frequency and amplitude as that of the full scale bridge, the actual method could lead to inaccurate flutter predictions.

In order to improve the actual mathematical representation of the flutter phenomenon, a few studies propose the use of

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Table 1
Characteristics of models.

Model	Width (*B*) (m)	Depth (*D*) (m)	*t*1 (m)	*t*2 (m)	*c* (m)	*e* (m)
Pi_1in	0.306	0.0387	0.00635	0.009525	0.0254	0.0076
Pi_2in	0.306	0.0387	0.00635	0.009525	0.0508	0.0056

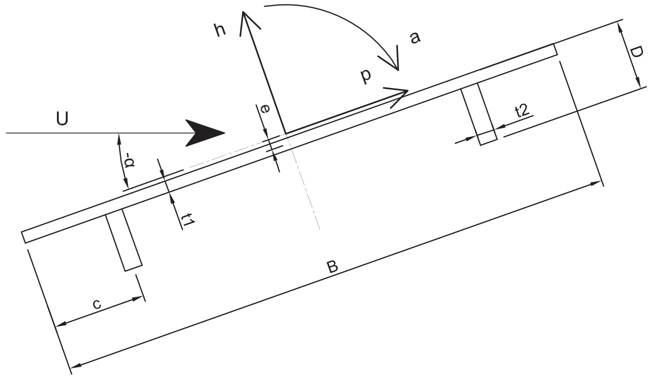

Fig. 1. Sign convention and definitions.

Table 2
Theoretical nominal speeds and accelerations tested.

DOF	Speed[a]	Acceleration[b]
Sway	18, 49, 77, 110, 145, and 180	220, 900, 2045, 3845, 4690 and 5600
Heave	22, 61, 95, 170, 230 and 305	280, 1100, 2480, 4190, 4990 and 6230
Twist	6.5, 18, 45, 62, 82 and 105	84, 735, 1510, 2060, 2620 and 3200

[a] Speeds are in mm/s or °/s.
[b] Accelerations are in mm/s^2 or °/s^2.

Table 3
Theoretical amplitudes of forced motion.

DOF	Speed	Acceleration
Sway	8.0 mm	6.0 mm
Heave	10.0 mm	9.0 mm
Twist	3.0°	1.5°

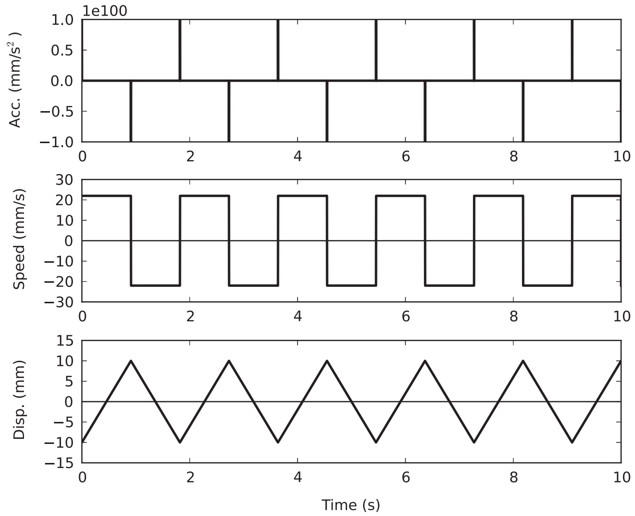

Fig. 2. Idealized displacement, speed and acceleration for the case of a constant absolute speed of 22 mm/s.

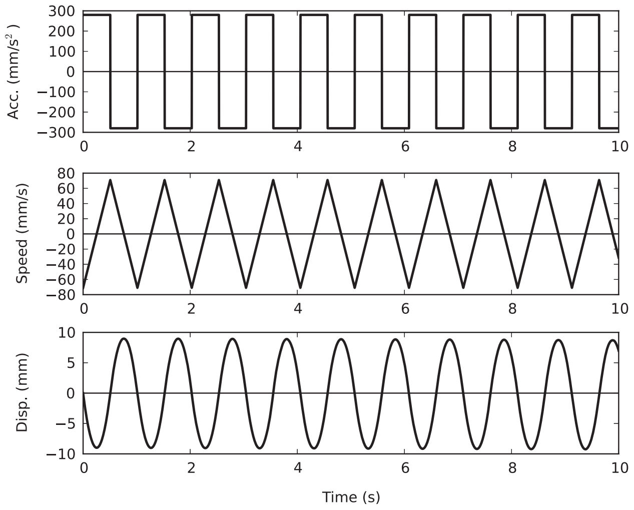

Fig. 3. Idealized displacement, speed and acceleration for the case of a constant absolute acceleration of 280 mm/s^2.

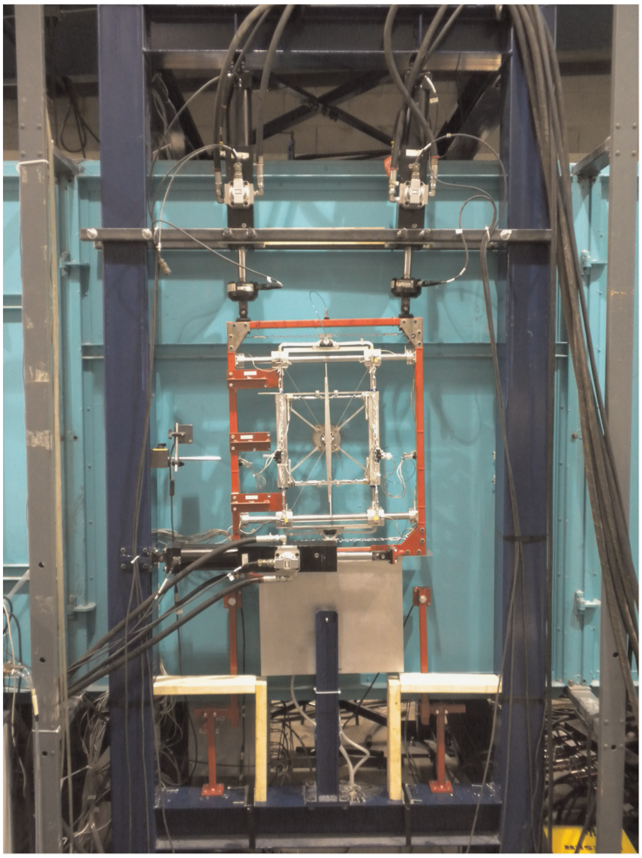

Fig. 4. Aerodynamic balance set for forced motion.

nonlinear transient analysis (Caracoglia and Jones, 2003; Chen et al., 2000; Kumarasena, 1990; Scanlan et al., 1974; Zhang et al., 2011). Each time, modal flutter derivatives are extracted and modified, generally using indicial functions, in order to use them in a nonlinear transient analysis. According to Caracoglia and Jones (2003), the determination of indicial functions for bluff bodies is difficult and even questionable. These functions were shown to be critical by Zhang et al. (2011) since they could highly affect the results of the nonlinear transient analysis.

The objective of this paper is to propose a new approach for the extraction aerodynamic matrices in time domain. An experimental

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