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The transient temporal response of a flexible bridge deck subjected to a single gust

X. Amandolese [a,b,*], P. Hémon [b], S. Manzoor [b]

[a] Département ISME, CNAM, Paris, France
[b] LadHyX, Ecole Polytechnique-CNRS, Palaiseau, France

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ABSTRACT

Temporal simulations are increasingly performed in wind effects analysis of flexible structures. By comparison with classical techniques such as spectral methods, temporal simulations provide the advantage of easily combining different kinds of loads, can take nonlinearities into account and also provide the only way to reproduce transient behaviors. In that context this study deals with the transient response of a two-degrees-of-freedom streamlined bridge deck section subjected to a single gust. Experimental evidence of the potentially high level of transient energy amplification due to that kind of extraneous excitation have been recently demonstrated for an airfoil section and for a streamlined bridge deck section, below the critical coupled-mode flutter wind speed. The present study then focuses on the validation of a time-dependent model, based on a simple formulation of both the motion-dependent and the buffeting forces, for catching that kind of transient behavior. A parametric study is also made in order to highlight the impact of the pitch–plunge frequency ratio on the energy amplification below the critical condition.

1. Introduction

Wind-induced responses of flexible structures encountered in civil engineering are traditionally studied using frequency domain approaches. Based on linear formulations of motion-dependent and buffeting loadings, spectral methods are generally sufficient for catching the critical parameters for the onset of flutter or calculating the variance associated with the dynamical response to a stationary turbulent wind [1,2].

Meanwhile, time domain analysis of wind effects on structures has been increasingly performed in recent years. By comparison with spectral methods, temporal simulations provide the advantage of easily combining different kinds of loads, can take structural and/or aerodynamic nonlinearities into account and also provide the only way to reproduce transient behaviors. A time domain approach has been successfully used in [3] for the analysis of flutter and buffeting responses of bridges. Effects of turbulence and aerodynamic nonlinearity have been pointed out in [4]. More recently, Costa et al. [5] proposed a wind–bridge interaction study using a time domain approach.

In the present paper we focus on a new type of short-term instability that has been recently highlighted in the field of fluid-structure interactions: the transient growth response to an initial perturbation before coupled-mode flutter. Theoretically studied in [6], this short-term energy growth can lead to substantial amplitude motion, even in a stable dynamical system, due to the non-orthogonal modes involved in the system. It is strongly dependent on the initial conditions.

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[*] Correspondence to: LadHyX, CNRS-Ecole Polytechnique, F-91128 Palaiseau, France. Tel.: +33 1 69 33 52 86; fax: +33 1 69 33 52 92.
E-mail addresses: xavier.amandolese@ladhyx.polytechnique.fr (X. Amandolese), pascal.hemon@ladhyx.polytechnique.fr (P. Hémon), sherry.manzoor@gmail.com (S. Manzoor).

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Table 1
Structural parameters of the two different bridge deck sections studied.

	f_z/f_α	f_α (Hz)	f_z (Hz)	k_α (N m/rad)	k_z (N/m)	J_O (kg m^2)	m (kg)	η_α (%)	η_z (%)
Case A	0.62	7.12	4.43	1.33	519.36	6.64 e^{-4}	0.66	0.3	0.08
Case B	0.44	8.00	3.56	1.67	309.16	6.61 e^{-4}	0.62	0.24	0.07

Experimental evidence of transient growth of the energy before coupled-mode flutter has been recently demonstrated for an airfoil section in [7] and a streamlined bridge deck section [8,9] subjected to mechanical or gust perturbation. Those results have shown that short-term energy amplification of the initial energy can reach a factor of more than 5 and can even trigger flutter instability in the case of nonlinear structures [10].

In that context, the present study deals with the transient response of a two-degrees-of-freedom bridge deck section subjected to a single gust. A rigid bridge deck section is flexibly mounted in heave and pitch in a steady air flow. The velocity is maintained under the critical condition, i.e. below the coupled-mode flutter critical wind speed. A superimposed single gust produces an initial excitation. The experimental setup and parameters are first detailed. Then a time-dependent model, based on a simple formulation of both the motion-dependent and the buffeting forces is presented. Computed results are compared with the experimental results. Finally, a numerical parametric study is done in order to highlight the impact of the pitch–plunge frequency ratio on the energy amplification below the critical flutter wind speed.

2. Transient wind tunnel tests

2.1. The experimental setup and identification of parameters

The main points of the experimental setup are recalled here. Further details concerning the experimental procedure can be found in previous work [8,9]. The bridge deck section is flexibly mounted in heave and pitch in a closed wind tunnel with the setup shown in Fig. 1. The two degrees of freedom $z(t)$ and $\alpha(t)$ are measured using laser displacement sensors connected to an acquisition system.

The elastic center of the deck section model is located at its gravity center, i.e. the mid-chord. The equations of motion for this structurally non-coupled two-degrees-of-freedom system can then be expressed as follows [11]:

$$\begin{aligned} &m\ddot{z} + 2m\eta_z\omega_z\dot{z} + k_z z = F_z, \\ &J_O\ddot{\alpha} + 2J_O\eta_\alpha\omega_\alpha\dot{\alpha} + k_\alpha\alpha = M_O. \end{aligned} \tag{1}$$

Assuming that the structural damping is small, the eigenvalues can be written in the form

$$\lambda_\alpha = \omega_\alpha^2 = (2\pi f_\alpha)^2 = k_\alpha/J_O; \qquad \lambda_z = \omega_z^2 = (2\pi f_z)^2 = k_z/m. \tag{2}$$

Structural parameters are identified for each degree of freedom under zero wind velocity. Both the natural frequencies f_z and f_α are obtained by spectral analysis. A static weight calibration technique is used to assess the stiffnesses k_z and k_α. The inertia J_O and mass m are then deduced, using

$$m = k_z/\lambda_z; \qquad J_O = k_\alpha/\lambda_\alpha. \tag{3}$$

Pure structural damping values η_z and η_α are determined using a standard decrement technique in free-decay tests under the zero-wind condition.

In the present study two different cases characterized by two different frequency ratios f_z/f_α between the heaving and pitching motions are tested. The structural parameters are summarized in Table 1.

The gust is produced by a flap mounted upstream from the test section. It is pre-tensioned with a spring and suddenly released. A typical time history of the perturbation of the flow velocity is plotted in Fig. 2, where $\bar{U}$ is the mean velocity, $u(t)$ and $w(t)$ being the longitudinal and vertical perturbations respectively. The flap generates a transient short impulse in the wind velocity, leading to a unique peak in the longitudinal component u, and two opposite peaks in the vertical component w. The time duration of this perturbation is about 0.05 s, which is three times below the typical period of the system.

2.2. Transient results

Because of the aerodynamic loading, a two-degrees-of-freedom bridge deck section can experience coupled-mode flutter instability above a critical velocity U_c. For both Case A and Case B the critical wind speed has been experimentally measured, at respectively 16.1 and 21.3 m/s. The responses of both the section model subjected to mechanical excitation (a sudden release of an initial pitch angle) or gust excitation (produced by the upwind flap) are then studied for different mean velocities below the critical condition.

For each test, the mechanical energy of the system, defined as the sum of the kinetic energy and the potential energy, is computed from the measurements of z and α such that

$$E(t) = \frac{1}{2}m\dot{z}^2(t) + \frac{1}{2}J_O\dot{\alpha}^2(t) + \frac{1}{2}k_z z^2(t) + \frac{1}{2}k_\alpha\alpha^2(t). \tag{4}$$