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Empirical modelling of the bifurcation behaviour of a bridge deck undergoing across-wind galloping

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ABSTRACT

This work presents an empirical model capable of describing the galloping bifurcation behaviour of a bridge deck. It is based on a general polynomial form proposed by Novak, which we limit to the 5th order. The advantage of choosing this function for modelling the vertical force coefficient is that the asymmetry of the even terms is enforced in order to reproduce the sub-critical aeroelastic behaviour of the bridge deck. The coefficients of the polynomial are identified from several pairs of displacement amplitudes and the corresponding airspeeds, measured in a wind tunnel during dynamic tests on the sectional bridge model. The identification is carried out using a first order harmonic balance technique. A stability analysis is presented in order to highlight the need for such a model to capture the complete bifurcation behaviour of the system. The resulting force coefficient of this full order model is compared to the well known models of Parkinson and Novak. Finally, the concept universal of the curve is used in order to discuss the galloping responses of square and rectangular cylinders, in comparison to that of the bridge deck.

1. Introduction

The phenomenon of galloping of bluff sections has been investigated by a large number of researchers, using both basic shapes, such as rectangular or square cylinders and engineering structures (bridge decks or towers). Since the seminal work by Parkinson and his co-workers (Parkinson and Smith, 1964; Parkinson, 1989), there have been many studies addressing various issues, such as aerodynamic modelling (Ge et al., 2002; Luo et al., 2003), multiple degree-of-freedom structures (Pheinsusom et al., 1989), oscillation control or suppression (Alam et al., 1995; Ogawa et al., 1997) and various case studies (Kazama et al., 1993; Yoshizumi and Inoue, 2002; Hirai et al., 1993). Nevertheless, few attempts have been made to advance the theoretical understanding of the phenomenon further than the first order quasi-steady theory proposed by Parkinson and used many times since then, in several variants. In particular, the complete bifurcation behaviour of a system undergoing galloping oscillations has rarely been addressed, except in the works of Novak (1969, 1972), van Oudheusden (1995) and Vio et al. (2007).

In this work, we concentrate on the general polynomial form proposed by Novak (1972) where a higher order polynomial model is presented to improve the quasi-steady modelling of galloping. We propose to limit the order of the polynomial to five and show that it is sufficient to model the complete bifurcation behaviour of a bridge deck section. The identification of the polynomial coefficients of the model is carried out using a first order harmonic balance method on the experimental dynamic measurements obtained in a wind tunnel.

2. Experimental data

The experimental data presented in this paper originate from a test campaign carried out by the authors in the wind tunnel of the University of Liège (Andrianne and Dimitriadis, 2011). A generic bridge deck section measuring 0.317 m wide by 1.2 m long is supported in a modified version of the set-up proposed by Sarkar et al. (2004). A set of 16 extension springs is used to replace the guiding bars and ball bearings in order to allow the deck to oscillate around its 6 degrees of freedom (DOFs). Note that amongst the 6 DOFs, mainly heaving motion was measured during the wind tunnel tests. The studied bridge section is rather bluff: it is composed of a trapezoidal beam supporting the deck made of two double traffic lanes. Windscreens with a equivalent porosity of 42% are present at both sides of the bridge. In addition, an acoustic panel is fixed on one side of the deck section. This barrier, impermeable to air, is modeled by an aluminum plate of 30 mm height and 2 mm thickness, along the whole span of the deck (see Fig. 1).

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The motion of the model is measured using four PCB capacitive accelerometers placed on the horizontal suspension arms. The acquisition frequency is set to 1 kHz and signals are filtered through a bandpass filter, limiting the frequency content between 2 Hz and 20 Hz.

The equation of the heaving DOF (y) is classically expressed as

$$m\ddot{y}+c\dot{y}+ky=F_y^{ext} \quad (1)$$

where m, c and k denote respectively the mass, damping coefficient and structural stiffness of the system. Their values are equal to 11.9 kg/m, 9.0 kg/s/m^2 and 10,066.7 N/m^2 respectively. The term F_y^{ext} on the right hand side of this equation corresponds to the external forces per unit length applied on the heave DOF of the system. The main purpose of this work is to model this term as a function of the structural velocity $\dot{y}$, by writing

$$F_y^{ext}=\frac{1}{2}\rho V_\infty^2 BC_{F_y}(\alpha(t))$$

where ρ is the air density, V_∞ is the free stream airspeed, B is the chord of the bridge deck, C_{F_y} is the non-dimensional aerodynamic force coefficient and $\alpha(t)$ is the time-varying angle of attack. After making the assumption that the vibration amplitude of the bridge is small, the angle of attack can be approximated by

$$\alpha(t)=\alpha_s+\frac{\dot{y}}{V_\infty}$$

where $\dot{y}<<V_\infty$ and α_s is a constant static angle of attack of the bridge deck with respect to the oncoming flow. Following classic galloping analysis, we can assume that $\alpha_s>>\dot{y}/V_\infty$ and expand the nonlinear force coefficient as a Taylor series around α_s so that

$$C_{F_y}(\alpha(t))=C_{F_y}(\alpha_s)+\left.\frac{\partial C_{F_y}}{\partial\alpha}\right|_{\alpha_s}\frac{\dot{y}}{V_\infty}+\frac{1}{2}\left.\frac{\partial^2 C_{F_y}}{\partial^2\alpha}\right|_{\alpha_s}\left(\frac{\dot{y}}{V_\infty}\right)^2+\ldots \quad (2)$$

where $C_{F_y}(\alpha)$ is now the static lift coefficient curve of the bridge deck, $C_L(\alpha)$. Fig. 2 shows the evolution of the lift and drag coefficients with the static angle of attack α_s. It is observed that the slope of the lift curve, $\partial C_L/\partial\alpha|_{\alpha_s}$ is positive for angles of attack between -15° and 4°. It becomes negative in the range of 4° to 24° and has its minimum negative value around 22°.

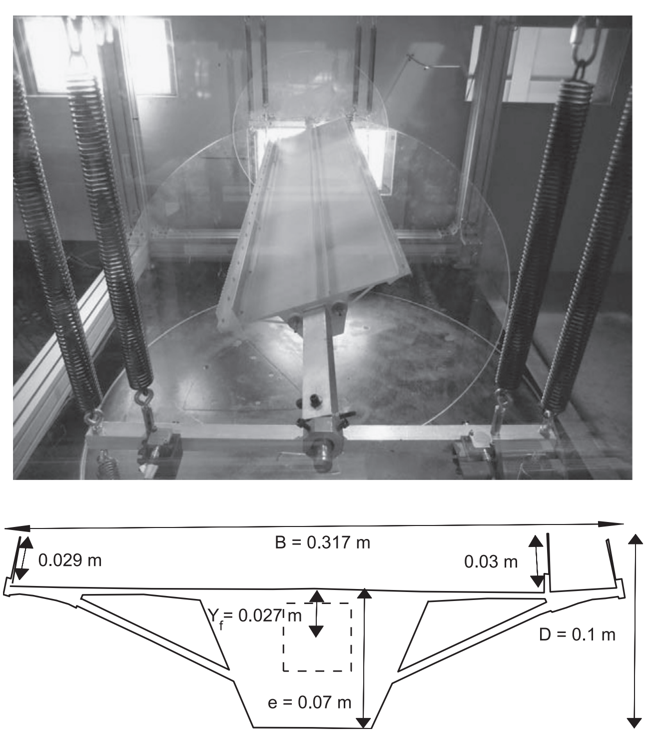

Fig. 1. Experimental set-up: suspension apparatus (upper figure) and deck geometry (lower figure).

According to the Den Hartog's criterion, no galloping phenomenon can be observed for positive values of the lift slope. For that reason, it was decided to investigate the galloping behaviour of the bridge section for $\alpha_s=19^\circ$, where large negative values of the lift slope are observed. Note that additional qualitative experiments were performed at different angles of attack (0°, 5°, 10° and 15°), but no galloping instability was observed. This can be explained by the relatively high damping coefficient (1.3%), which leads to large values of the critical galloping airspeed.

The recovered displacement response amplitude is presented in Fig. 3 in the form of a non-dimensional bifurcation diagram: evolution of the maximum reduced amplitude of the vertical motion with the non-dimensional airspeed. In this work, the bifurcation diagram is expressed in its universal form, as proposed by Novak (1969). For this purpose, the following non-dimensional quantities are introduced:

$$\eta=\xi\frac{n}{\beta}\quad U=V^*\frac{n}{\beta}$$

where ξ and U are themselves non-dimensional variables defined by $\xi=y/B$ and $V^*=V_\infty/(\omega B)$. Note that the multiplication ratio n/β is inversely proportional to the Scruton number (defined by $Sc=4\pi\beta m/\rho B^2$). Hence the variables used by Novak are equivalent to dividing the usual non-dimensional quantities η and V^* by the Scruton number, which is a key number in the field of fluid–structure interaction.

Introducing the usual dynamic parameters $\beta=c/2m\omega$ and $n=\rho B^2/4m$, with $\omega=\sqrt{k/m}$, it is possible to express the equation

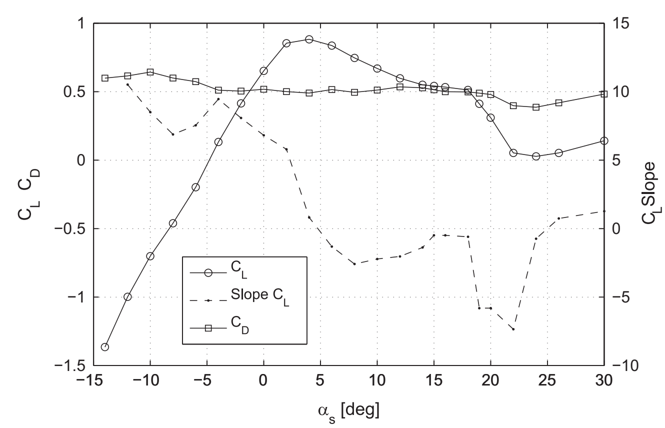

Fig. 2. Lift and drag coefficients of the bridge section.

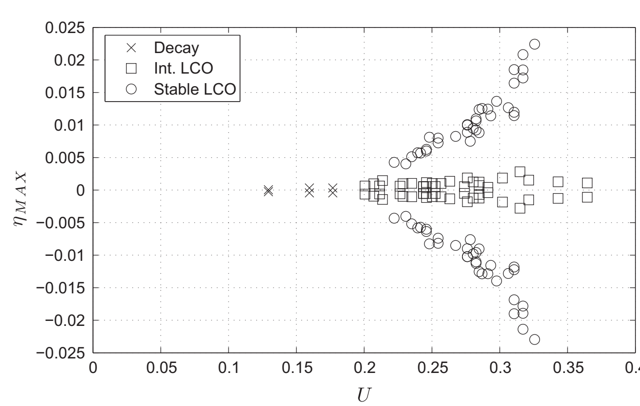

Fig. 3. Universal bifurcation diagram of the bridge deck.