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Coupling between a flag and a spring-mass oscillator

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ABSTRACT

In the context of energy harvesting we address the coupling between a flexible flag and its flagpole equipped so that it constitutes a spring-mass oscillator. An extensive set of experiments is carried out in wind tunnel for various flag and oscillator parameters. Results are analyzed in terms of frequency and amplitude of rotation of the flagpole. We report numerous configurations of coupling by frequency lock-in leading to resonance conditions. In the case of strong coupling, high amplitudes of rotation of the flagpole are reported, up to 75° peak-to-peak, over a large range of wind velocities. We also propose to characterize the strength of the coupling with a dimensionless rigidity $\tilde{B}$, which can be considered as the ratio of the flag bending rigidity to the stiffness of the oscillator.

1. Introduction

Harvesting energy from flapping flags is an idea that has been intensively considered during the last decade. Two mechanisms are generally proposed for the excitation of the flag: either an external forcing by an unsteady flow, such as the wake of a bluff body (Allen and Smits, 2001; Taylor et al., 2001), or an intrinsic forcing by a steady flow destabilizing the flag by flutter (Tang et al., 2009). Two technical strategies for harvesting electric energy have also been described in previous works, either distributed or localised. On the one hand, the deformation of the flag can be used, for instance by covering the flag surface with piezoelectric patches, as in the recent experimental and numerical studies by Doaré and Michelin (2011), Dunnmon et al. (2011), Giacomello and Porfiri (2011), Singh et al. (2012), Akcabay and Young (2012), Michelin and Doaré (2013), and Xia et al. (2015). On the other hand, the displacement of the flag can be used, then taking advantage of electromagnetic induction or triboelectricity as in the recent experimental and numerical studies by Gibbs et al. (2012), Stone et al. (2013), Howell and Lucey (2014), and Bae et al. (2014).

A key point is that energy transfers are favoured in the situation of resonance. More precisely, it has been shown numerically that there is a strong increase in the efficiency of the harvesting in the presence of a frequency lock-in, in the context of the coupling between a piezoelectric flag and an electrical oscillator (resistance-inductance) studied by Xia et al. (2015). Moreover, in the context of vortex-induced vibrations, the frequency lock-in between the wake vortices and a cylinder-oscillator is essential (Khalak and Williamson, 1999; Williamson and Govardhan, 2004) and is already concretely used for harvesting energy from water currents (see Bernitsas et al., 2008). By comparison with systems based on flapping flags, a wake of vortex can be seen as the analogue of a flag. Both exert a periodic forcing on the oscillator, which can be significantly enhanced by the oscillator motion in the lock-in region.

In this paper, we focus on the intrinsic flutter instability of flags and we trigger frequency lock-in conditions between flapping flags and oscillating flagpoles, while varying the parameters of the flag and oscillator. Results are analyzed in terms of frequency and amplitude of rotation of the flagpole.

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2. Experiments

2.1. Experimental set-up

An Eiffel-type wind tunnel is used with wind velocities ranging from 3 to 20 m s^{-1} at a low turbulence level (0.4% over this velocity range). The wind tunnel has a rectangular test-section: width × height=260 mm × 240 mm. The flag is clamped inside of a flagpole of thickness 4 mm and height 140 mm. In our experiments, the Reynolds number based on the flag length (L) falls in the range $\mathrm{Re}_L = 1 \times 10^4 - 4 \times 10^5$.

The flagpole is not clamped in the wind tunnel. Rather, it is guided by two ball bearings, Fig. 1, making it free to rotate. An inertia bar and a set of linear springs are attached to the flagpole to modelize an elementary spring-mass oscillator.

The instantaneous amplitude of rotation of the flagpole is characterized by the rotation angle $\theta(t)$ between the inertia bar and the normal to the wind, Fig. 1(a). Since the flag is clamped to a rigid flagpole, the angle $\theta(t)$ is also the rotation angle of the leading edge of the flag. It is measured with a laser sensor recording 1024 acquisitions per second with an error lower than 1% in the range of angle from −60° to 60°. In this paper, the fluctuations of $\theta(t)$ are reported with the standard deviation $\sigma_\theta = \sqrt{\langle\theta^2\rangle - \langle\theta\rangle^2}$. The acquisition duration is 24 s, which is sufficient to record more that 100 flapping periods. Concerning the frequency analysis, noise is reduced by treating independently blocks of 8 s (with an overlap: 50%); the resulting frequency resolution is then 1/8 Hz.

2.2. Characteristics of the flag and spring-mass oscillator

The flapping frequency of flags must be sufficiently low to be coupled with the (low frequency) spring-mass oscillators, whose natural frequency can be varied between 1 Hz and 20 Hz. We used paper sheets (120 g m^{-2}, thickness d=153 μm) and steel sheets (thickness d=54, 77 or 103 μm). The mass densities of these sheets are respectively ρ_s = 790, 7290, 7620 and 7680 kg m^{-3}. The width of the flags is unchanged (H=100 mm), while the flag length is varied in the range L=60–300 mm. The size of the flags is chosen to limit blockage effect in the wind tunnel.

We have used two inertia bars, depending on the natural frequency needed: a thick aluminium bar and a thin carbon fiber bar. The moment of inertia J_{osc} of the system with the aluminium bar is 1.7×10^{-4} kg m^2, whereas it is 9.2×10^{-5} kg m^2 with the carbon fiber bar. In practice, the carbon fiber bar is quite unique to be both rigid and light (Ashby, 2000). Indeed, we pay a particular attention to the fact that a flexible inertia bar could interact with the flag. Here the bending rigidity of the bar is always 100 times larger than the stiffness of springs. If the natural frequency of the oscillator needs to be precisely adjusted, then additional masses may be placed along the inertia bar, allowing a variation of the inertia moment J_{osc} between 9.2×10^{-5} kg m^2 and 8.4×10^{-4} kg m^2.

We used linear spring with stiffness in the range 0.05–0.28 N mm^{-1}, leading to stiffness in rotation varying in the range C_{osc} = 0.28–2.3 N m rad^{-1}. For keeping the symmetry of the system, a particular attention is devoted to place identical springs in parallel, at the same distance from the axis of rotation.

The mechanical oscillator attached to the flagpole is irremediably damped. After a small perturbation of the system without flag, the exponential decrease of the rotation angle that we observed suggests that the damping is essentially viscous (Landau and Lifshitz, 1976, p. 75). The damping is therefore expressed by a dimensionless damping ratio ζ^*_{osc} (Landau

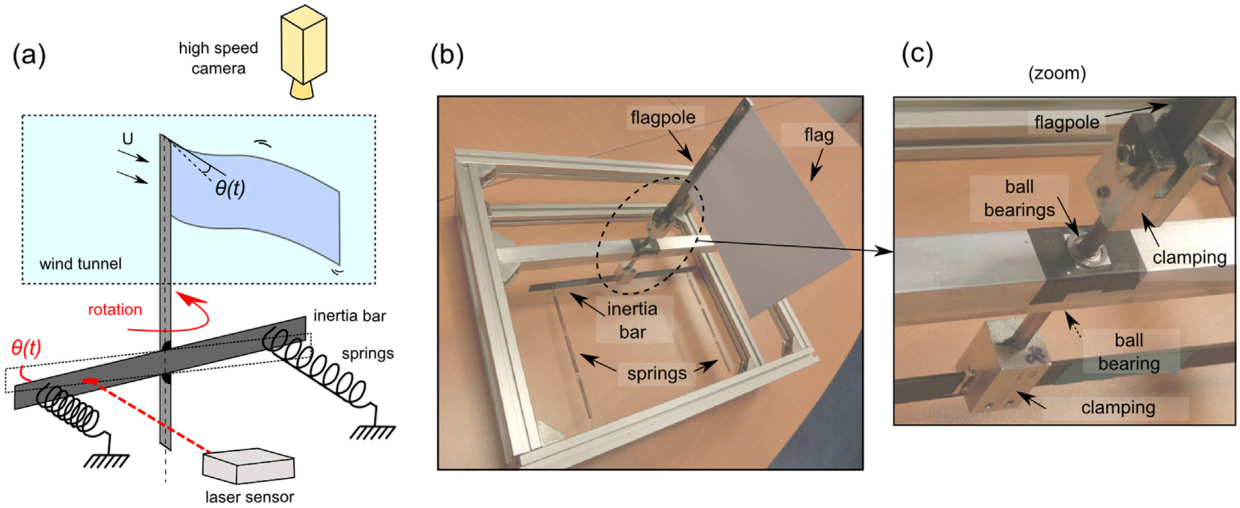

Fig. 1. Experimental set-up. (a) Schematic representation of the experiment. The flagpole is attached to a spring-mass oscillator, which is out of wind-tunnel. A laser sensor measures the angle of rotation θ of the rotating inertia bar fixed to the flagpole. (b,c) Photographs of the experimental set-up (here the whole system is out of wind-tunnel), where it can be seen that the flagpole is guided by ball bearings.