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On the efficiency of energy harvesting using vortex-induced vibrations of cables

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ABSTRACT

Many technologies based on fluid–structure interaction mechanisms are being developed to harvest energy from geophysical flows. The velocity of such flows is low, and so is their energy density. Large systems are therefore required to extract a significant amount of energy. The question of the efficiency of energy harvesting using vortex-induced vibrations (VIV) of cables is addressed in this paper, through two reference configurations: (i) a long tensioned cable with periodically-distributed harvesters and (ii) a hanging cable with a single harvester at its upper extremity. After validation against either direct numerical simulations or experiments, an appropriate reduced-order wake-oscillator model is used to perform parametric studies of the impact of the harvesting parameters on the efficiency. For both configurations, an optimal set of parameters is identified and it is shown that the maximum efficiency is close to the value reached with an elastically-mounted rigid cylinder. The variability of the efficiency is studied in light of the fundamental properties of each configuration, i.e. body flexibility and gravity-induced spatial variation of the tension. In the periodically-distributed harvester configuration, it is found that the standing-wave nature of the vibration and structural mode selection plays a central role in energy extraction. In contrast, the efficiency of the hanging cable is essentially driven by the occurrence of traveling wave vibrations.

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1. Introduction

Innovative energy harvesting devices are being developed to extract energy from geophysical flows such as wind or marine currents. The most common way to extract this energy is to convert it into the rotary motion of a dedicated structure, as wind turbines or marine turbines (Nishino and Willden, 2012; Bahaj, 2013; Batten et al., 2013). Even if these technologies are now mature from an industrial point of view, several other mechanisms to harvest this energy are currently being studied.

Among them, a specific class is based on flow-induced vibrations (Blevins, 1990; Naudascher and Rockwell, 1990). Energy harvesting through fluid–elastic instabilities has been investigated, such as galloping (Barrero-Gil et al., 2010), airfoil coupled-mode flutter (Peng and Zhu, 2009; Boragno et al., 2012) and flutter in an axial flow (Tang et al., 2009; Singh et al., 2012b,a;

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Michelin and Doaré, 2013). Vortex-induced vibrations (VIV), a strong coupling between the solid dynamics and its fluctuating wake, are another interesting mechanism to extract energy from geophysical flows (Yoshitake et al., 2004; Barrero-Gil et al., 2012). Bernitsas et al. (2008) for instance developed the VIVACE device to harvest energy by VIV of elastically-supported rigid cylinders.

A quantitative criterion is necessary to compare the performances of all these emerging technologies. As in Barrero-Gil et al. (2010), Bernitsas et al. (2008) or Hobbs and Hu (2012), we define the efficiency of the harvesting, η, as the ratio between the time-averaged extracted power $\langle\mathcal{P}\rangle$, where $\langle\cdot\rangle$ stands for time-averaged quantities, and the energy flux across the cross-flow section $\mathcal{A}$ of the device, $\mathcal{P}_0$,

$$\eta=\frac{\langle\mathcal{P}\rangle}{\mathcal{P}_0}=\frac{\langle\mathcal{P}\rangle}{\frac{1}{2}\rho\mathcal{A}U^3}, \tag{1}$$

where ρ and U are respectively the fluid density and the flow velocity. There are of course many other ways to define the efficiency of an energy harvesting device, see for instance Zhu et al. (2009) or Doaré and Michelin (2011). In such geophysical flows, the energy density $(\rho U^3/2)$ is low, of the order of 500 W/m^2 for typical wind speed (10 m/s) or current speed (1 m/s). A large area $\mathcal{A}$ is thus needed to access large quantities of energy. This can be achieved either by considering many short devices, as in Bernitsas et al. (2008), or one single large structure, as considered in the present paper.

In the specific domain of VIV, such large structures have been extensively studied for offshore engineering issues (Baarholm et al., 2006; Tognarelli et al., 2008; Mukundan et al., 2009; Modarres-Sadeghi et al., 2010). VIV of long cables consist of vortex-induced waves, which can be stationary or traveling (Vandiver, 1993). The excitation of the structure through lock-in, i.e. the synchronization between the vortex shedding and the body oscillation, may occur successively for each vibration mode of the cable (Chaplin et al., 2005; King, 1995).

Placing long flexible structures, such as cables, in a cross-flow seems like a promising way to harvest energy from low velocity geophysical flows. Yet the corresponding dynamics is much more complex than that of a rigid body, and it is necessary to explore how the efficiency depends on the parameters of the system. In the present paper, this question is addressed through two reference configurations, using a classical reduced-order model, which is validated here in comparison with Direct Numerical Simulations (DNS) and experiments. The configuration of a tensioned cable with periodically-distributed harvesters is first investigated to study how the distance between harvesters and their respective intensity influences the efficiency. To analyze the impact of a single harvester and to show the feasibility of the proposed energy harvester in practice, the second configuration is a hanging cable with one harvester at its upper extremity, for which the tension is induced by gravity. Section 2 describes the model used throughout the paper. In Section 3, the case of the elastically-mounted rigid cylinder is considered. Sections 4 and 5 address the two reference cases of a cable with harvesters, introduced above.

2. Model

2.1. A reduced-order wake-oscillator model

A comprehensive study of the impact on the efficiency of the system parameters using experiments or DNS would be very time consuming and computationally expensive. A reduced-order model is therefore used in this study, based on the ones that have been developed for VIV since Hartlen and Currie (1970). These models have been extended to long cables (Violette et al., 2007; Xu et al., 2008; Srinil, 2010), and have been proven to predict accurately the main features of their dynamics, as well as some of their complex features like mode switching (Violette et al., 2010). In these models, the fluctuating lift exerted by the wake on the bluff body is modeled by a single variable, $q=2C_L/C_{L0}$, where C_L is the instantaneous lift coefficient and C_{L0} is the lift coefficient if the solid were fixed. In the wake-oscillator considered here, the evolution of q is assumed to follow a Van der Pol oscillator equation,

$$\ddot{q}+\varepsilon(q^2-1)\dot{q}+q=f_s, \tag{2}$$

where $\dot{()}$ stands for the derivative with respect to the dimensionless time $t=\omega_f T$, where T is the time and $\omega_f=2\pi\,\mathrm{St}\,U/D$ is the Strouhal shedding frequency, St is the Strouhal number, U is the flow speed and D is the solid diameter. Eq. (2) is coupled with the solid equation by the forcing term f_s. Facchinetti et al. (2004) showed that an inertial coupling provides an accurate representation of VIV, using $f_s=A\ddot{y}$, where $y=Y/D$ is the solid dimensionless transverse displacement. In the following, the values $\varepsilon=0.3$ and $A=12$ are used (Facchinetti et al., 2004), unless otherwise specified.

2.2. Model for the energy harvesters

Energy harvesting induces a loss of energy for the fluid–solid system. It is thus represented in the remainder of the paper by a local viscous damping force, whose intensity is a key parameter of the problem.

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