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Energy harvesting from different aeroelastic instabilities of a square cylinder

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ABSTRACT

This paper presents an experimental and numerical investigation of the power extraction from the oscillations of a square beam due to aeroelastic instabilities. The energy harvesting is performed using a coil-magnet arrangement connected to a variable resistance load with the target objective to auto-power a remote sensor. Two aeroelastic phenomena are investigated: Vortex Induced Vibration (VIV) and cross-flow galloping. The first instability (VIV) is analyzed on a free-standing vertical structure. A second experimental set-up is developed on a horizontal square cylinder supported by springs, free to oscillate vertically as a rigid body. In this case, both galloping and VIV interact, leading to interesting characteristics in order to harvest energy from the wind. The behavior of each electro-mechanical aeroelastic system is investigated for different reduced wind speeds and load resistances in a wind tunnel. Observed efficiencies are rather low, but large enough to power a remote sensor with an adapted measuring strategy. Both harvesting systems are then studied numerically using a wake oscillator model (for VIV) coupled to a quasi-steady model (for galloping) and an electric model (for the harvester). This mathematical model is used to extend the parametric space and to highlight the effectiveness of the high stable branch of the VIV-galloping curve to harvest energy.

1. Introduction

The amount of smart remote sensors has constantly increased over the last years. The objective of such sensors is to obtain information about the environment (temperature, luminosity, noise, humidity, …) or to take part to communication networks. A main drawback of such systems is the need to supply power: conventional power supplies, such as battery or supply cables, consist in the main obstacle to reach a higher integration of microsystems in engineering applications. The energy harvesting concept can relax this constrain by using free and renewable energy to power ultra-low power devices.

The objective of this work is to study the potential of simple aeroelastic systems to harvest energy from the wind. One of the difficulty concerns the coupling of the harvesting device to the aeroelastic system, which might change the behavior of the global electro-aeroelastic model. Many research works have been dedicated to this topic. Some of them are purely experimental (Sousa et al., 2011; Hémon et al., 2017; Bernitsas et al., 2008), numerical (Tang et al., 2009; Vicente-Ludlam et al., 2014) or in-between, without modelling the harvester (Barrero-Gil et al., 2012).

In the scope of this work, we first focus on an experimental investigation on two types of aeroelastic phenomena: (i) VIV of a vertical structure and (ii) VIV-galloping of a horizontal structure. A full electro-aeroelastic model is then used to push further the analysis by expanding the parameter space and discussing the corresponding energy harvesting possibilities.

2. Methodology

For each configuration, a wind tunnel test campaign is carried out to measure the amplitude of motion and the electrical power (P_{EH}) as a function of the reduced velocity, for different values of the load resistance of the harvesting device. In parallel, the electro-aeroelastic behavior is investigated by adequate numerical models: For VIV, the model proposed by Tamura (Tamura and Matsui, 1979) is selected. This model is a wake oscillator type (two degrees of freedom), having the advantage to involve parameters that can be related to static aerodynamic quantities. For galloping, the classical Parkinson's model using a fifth order polynomial form of the vertical force coefficient is selected

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(Parkinson and Smith, 1964). The empirical constants of this model are taken from the works of Nakamura (Nakamura and Mizota, 1975).

These non-linear models allow to capture the complex aeroelastic behavior of the systems (lock-in for VIV and subcritical bifurcation for galloping). In the case of the horizontal beam, where VIV and galloping are expected to interact, the two models are coupled to reproduce this interaction effect, which changes the form of the traditional bifurcation diagram (Mannini et al., 2014). The models are used to quantify the potential energy transfer between the flow and the structure. Barrero et al (Barrero-Gil et al., 2012) and Vincente-Ludlam et al. (Vicente-Ludlam et al., 2014) proposed a similar approach using fluid force models based on experimental data.

3. Wind tunnel models

The tests are performed in the multi-disciplinary wind tunnel of University of Liège, in uniform low turbulence flow conditions (TI<0.2%). Two experimental apparatus are used in this study: a vertical set-up (Fig. 1) and a horizontal set-up (Fig. 2). The set-ups consist of square aluminium tube with a side of 50 mm (noted D), a thickness of 2 mm and a length of 1650 mm and 1340 mm for the vertical and horizontal apparatus respectively. The beam is simply clamped on the floor of the test section in the case of the vertical set-up, resulting in a cantilever beam. For the second set-up, the beam is supported horizontally by two thin rectangular beams, playing the role of springs. In this case the motion of the square cylinder is purely vertical thanks to the important length of the spring beams. The harvesting device consists of a coil-magnet assembly mounted at the tip of the model for the vertical set-up (Fig. 1) and on one side of the model for the horizontal set-up (Fig. 2).

The structural characteristics of each set-up are identified through free responses (hammer impacts) imposed to the beam (see Table 1). A laser displacement sensor is used to measure the motion of the model. A variable load resistance is connected to the coil-magnet device. A voltmeter measures the voltage through the load resistance (V_L) and the electrical power produced by the harvesting system is calculated by $P_{EH}=V_L^2/R_L$.

4. Experimental results

The VIV response and electrical power extracted by the coil-magnet assembly in the case of the vertical structure are presented in Fig. 3 as a function of the reduced velocity ($U^* = \frac{U}{fD}$) and for different values of the load resistance. It is observed that the VIV oscillations starts around U*~7.7–1/0.13 (shown as a grey square marker), where St = 0.13 is a good estimate of the Strouhal number of the square cylinder in this range of Reynolds number. The lock-in range is equal to $\Delta U^* = 2.5$, which is small because of the large value of the Scruton number of the system ($Sc = \frac{2\pi m\xi}{\rho D^2} = 10.5$). The effect of the load resistance on the amplitude of vibration and lock-in range is low.

The maximum electrical power is reached around U* ~8 and for a load resistance around 400Ω. The optimum value of the load resistance matches the resistance of the coil (R_C = 406Ω) in accordance with the Maximum Power Transfer Theorem.

Fig. 4 shows the galloping response and power output as a function of the reduced velocity for the horizontal set-up. In this figure the grey and black square markers correspond to the critical VIV velocity and the quasi-steady prediction of the galloping velocity respectively. The curve shows no clear VIV response. Instead, the galloping phenomenon is triggered by the VIV instability and the resulting bifurcation branch follows linearly the reduced velocity U*. This close vicinity between the two critical velocities is interesting because the initiation of the vibration and hence energy production is less sensitive to the energy extraction.

It is observed that the load resistance has no effect on the resulting oscillation amplitude but a strong effect on the extracted power. The optimal value of the load resistance is R_L = 255Ω, matching the internal resistance of the coil (R_C = 257Ω), similarly to the case of the vertical set-up presented above.

Fig. 5 presents the efficiency (P_{EH}/P_{WIND}) in the plane (U*,R_L). The wind power being defined by the kinetic energy flux of air passing through the area swept by the oscillating square cylinder. In the left plot, the VIV optimal efficiency is clearly localized on a peak, centered on (8,400). Beyond this peak (U*>10), no more energy can be extracted by the system since the lock-in phenomenon ended. In the right plot, the situation is different: beyond the critical velocity (U* = 10), the system is unstable and energy can be harvested up to U* = 30 (which is the limit of the wind tunnel test). Nevertheless, the optimum harvesting region lies around U* = 15 and R_L = 250Ω. This is a clear difference between the two harvesting apparatus.

On the energy harvesting point of view, the power outputs of the set-up are small but large enough to power small size sensors which are able to operate with 1 mW, with an adapted strategy. The efficiency is low: 10^{-6} for the VIV set-up and 10^{-3} for the VIV-galloping system. This result brings out the poor efficiency of the current design choice for the coil/magnet assemblies to harvest the mechanical energy of motion. The model presented in the next section will highlight possible improvements.

5. Modelling

A mathematical model of the energy harvesting system is built by coupling an electromechanical galloping system, as proposed by Vicente et al. (Mannini et al., 2014) to the vortex induced vibration model proposed by Tamura (Barrero-Gil et al., 2012). The model consists of three non-dimensional equations:

$$\ddot{Y} + \left(2\,\zeta_s + \frac{n(f+D)\nu}{S_*}\right)\dot{Y} + Y = -\frac{fn\nu^2\theta}{S_*^2}\frac{F_Y}{M\omega^2 D} - \frac{k_E}{M\omega^2 D}I \qquad (1)$$

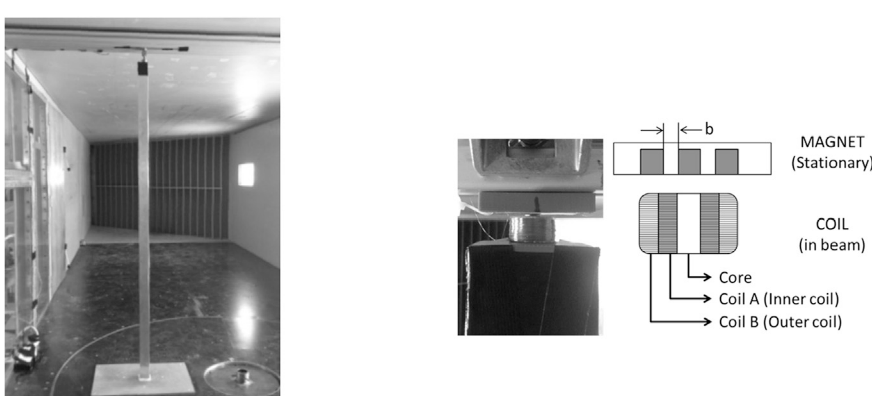

Fig. 1. Vertical experimental set-up installed in the test section (left) - Coil/magnet assembly (right).